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AT-SEA EVALUATION OF THE OBSCURATION CHARACTERISTICS OF A HYGROSCOPIC AEROSOL SMOKE PRODUCED BY THE CY85A PYROTECHNIC

By

J.T. Hanley, E.J. Mack and B.J. Wattle

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For the past six years, Calspan, in collaboration with the Naval Research Laboratory (NRL) and the Naval Weapons Center (NWC) has conducted a laboratory evaluation of the extinction characteristics of the CY85A pyrotechnic and related formulations under development at NWC. The overall objective of the Navy program is the development of an effective screening agent to both visible and IR wavelength radiation utilizing pyrotechnically-generated hygroscopic aerosol. This year, under contract with NRL, Calspan participated in NRL's

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at-sea evaluation of the CY85A pyrotechnic smoke obscurant. The evaluation was conducted as one phase of NRL's Atmospheric Physics Cruise, 1983.

In general, the NWC pyrotechnics are formulated to produce smokes of alkali-halide salt particles upon combustion. Such particles are especially advantageous due to their hygroscopicity. When exposed to a sufficient level of ambient humidity the particles deliquesce to form solution droplets of approximately twice their original size and five times their original mass. Therefore, only a fraction of the resultant cloud mass (smoke screen) originates from the pyrotechnic, the remaining mass being supplied by atmospheric water vapor.

The specific objective of the current program was to evaluate the extinction characteristics of the CY85A pyrotechnic during the at-sea trial. Measurements were made of the smoke's mass loading, scattering coefficient, mass extinction coefficient, aerosol size distribution and chemical composition. Additionally, the at-sea measurements provided a means of evaluating the capability of large-scale chamber tests to adequately simulate the in-field extinction performance of the pyrotechnics.

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Section 1
INTRODUCTION

For the past six years, Calspan, in collaboration with the Naval Research Laboratory (NRL) and the Naval Weapons Center (NWC) has conducted a laboratory evaluation (References 1-5) of the extinction characteristics of the CY85A pyrotechnic and related formulations under development at NWC. The overall objective of the Navy program is the development of an effective screening agent to both visible and IR wavelength radiation utilizing pyrotechnically-generated hygroscopic aerosol. This year, under contract No. N00014-82-C-2108 with NRL, Calspan participated in NRL's at-sea evaluation of the CY85A pyrotechnic smoke obscurant. The evaluation was conducted as one phase of NRL's Atmospheric Physics Cruise, 1983.

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Results and measurements from the at-sea trials are discussed in Section 3. Details of instrumentation and procedures are provided in Section 2; while Appendix C presents photographic documentation. Detailed extinction and particle size data are provided in Appendices A and B, respectively. Conclusions and recommendations are discussed in Section 4.

Section 2

INSTRUMENTATION AND PROCEDURES

The measurements were obtained from aboard the USNS Lynch in the mid-Atlantic while en route from Charleston, South Carolina to the Canary Islands (see Figures C-1 and C-2, Appendix C). A total of ten tests were performed, each involving the aerosolization of a single canister containing a 160 pound payload of the CY85A pyrotechnic (see Figure C-6). The canisters were suspended off the stern of ship for combustion (i.e., aerosolization). Upon ignition with a small AgI ignitor, the 160 pound payload burned for approximately eight minutes.

The first of the burns was conducted under calm winds with the ship at rest in the water. Due to the heat released during the combustion of the pyrotechnic, the smoke from this burn pillared upward producing a smoke cloud high overhead with little smoke remaining at the surface (Figure C-9). To reduce this pillaring effect, the remaining burns were conducted with the ship underway so as to create a relative headwind of from 5 to 10 knots. Such a headwind was found to sufficiently dilute the heat of the pyrotechnic to produce a surface based smoke screen (Figures C-7 and C-8).

After the ship was placed on a course and speed to produce the 5 to 10 knot relative headwind, the pyrotechnic was ignited. As the pyrotechnic burned, the ship was turned in an attempt to intersect the smoke plume. As the tests proceeded, experience was gained in maneuvering the ship relative to the smoke plume and measurements were, in general, obtained in progressively denser and fresher smoke. To assess the extinction characteristics of the pyrotechnic smokes, measurements were made of the scattering coefficient, mass loading, aerosol size distribution and chemical composition. The specific instrumentation used to perform these measurements is discussed below and is summarized in Table 1. The shipboard locations of instrumentation and sampling sites are shown photographically in Appendix C.

Aerosol scattering coefficient measurements were obtained with Calspan's MRI Integrating Nephelometer for values less than 4 km^{-1}. For greater values of the scattering coefficient, data from NRL's HSS nephelometer (channel 2) are reported

TABLE 1

CALSPAN INSTRUMENTATION INSTALLED ON THE USNS LYNCH

TRANSATLANTIC/EUROPEAN COAST CRUISE -- MARCH-APRIL 1983

	Instrument	Parameter	Height Above Sea Surface
1.	Gardner Small Particle Detector	Aerosol Concentration (>.0025 μm diameter)	11 meters
2.	Thermo Systems Model 3030 Electrical Aerosol Analyzer	Aerosol Size Distribution (0.01 to 1.0 μm diameter)	11 m
3.	Royco Model 225 Particle Counter	Aerosol Size Distribution (0.47 to 10 μm diameter)	11 m
4.	MRI Integrating Nephelometer (Model 2050)	Scattering Coefficient (.1 - 100 x 10^{-4} m^{-1})	8.5 m
5.	Calspan Droplet Sampler (gelatin replication)	Drop Size Distribution (∼2 - 100 μm diameter)	6.7 m
6.	Foxboro Temperature System (4 sensors)	Sea Surface and Air Temperatures	sea sfc, 7 m, 14 m, 20 m
7.	Sling Psychrometer	Wet and Dry Bulb Temperatures	6 m
8.	Beckman-Whitley Wind System	Wind Speed & Direction	20 m
9.	Casella Cascade Impactors	Aerosol Samples for SEM Analysis	6.7 m
10.	Aerosol Filter Sampler	Mass Loading Determination and Chemical Analysis	6.7 m

when such data were available. The sensors for both instruments were mounted outdoors atop the instrument trailer (Figure C-4).

Aerosol mass loading was determined gravimetrically. Aerosol samples were drawn upon 0.3 um Nuclepore "aerosol" membrane filters at a rate of from 1 to 2 cfm. Flow rate was monitored with an in-line flow meter mounted downstream of the filter with readings corrected for filter pressure drop (also monitored). Prior to the cruise, each filter was preweighed on a Cahn 26 electro-balance. Upon return to Calspan, the filters were dessicated at 5% relative humidity and reweighed to determine the nominal (i.e., "dry") aerosol sample mass. Mathematic division of this mass by the sampled air volume yielded the nominal mass loading. The nominal mass extinction coefficient was then determined by averaging the scattering coefficient data obtained during the filter sampling period and dividing this value by the nominal mass loading.

The aerosol size distributions of the smokes were measured with three aerosol sizing instruments each covering a specific size range: A TSI model 3030 Electrical Aerosol Analyzer (EAA) for particles of diameter from 0.01 to 1.0 um; a Royco model 225 optical particle counter for particles from 0.47 to 10 um diameter; and a Calspan-fabricated Drop Sampler, a large particle gelatin slide impactor, for particles greater than approximately 2 um in diameter. The EAA and Royco were mounted in the instrument trailer drawing their sample air from an aspirated sample line which extended $\sim$3 m above the instrument trailer (Figure C-4, location J). The Drop Sampler was positioned on the bow rail for sample acquisition (Figure C-3, location E).

Due to high aerosol concentrations in the smokes and rapid concentration fluctuations resulting from inhomogneities and movement of the smoke relative to the ship, problems were encountered in the sampling of the smoke by the three aerosol sizing instruments. The EAA experienced the greatest sampling difficulty as this instrument was designed to sample aerosol concentrations which remain relatively constant over its $\sim$70 second sampling period. (The requirement of a constant aerosol concentration results from the sequential (as opposed to simultaneous) sampling of the EAA's eight size channels (0.01 - 1.0 um diameter) during its sampling cycle). As a result of these constraints, only four EAA size distribution measurements taken in the smoke plumes appeared suitable for analysis.

The Royco, typically operating on a one minute sampling interval simultaneously sized aerosol particles in each of its five size channels (0.47 - 10 um diameter) and thus, aerosol fluctuations were not a problem for this instrument. However, high aerosol concentrations did overload the Royco at times resulting in a limited amount of data loss under dense smoke conditions. Additionally, due to the potential for large particle aerosol loss in the Royco sample line, aerosol concentrations in the largest Royco channel (5.62-10 um diameter) are likely to be underestinates of the true concentration.

To assess the aerosol concentration of particles larger than could be properly evaluated by the Royco (i.e., $\gtrsim$5 um), the Calspan Drop Sampler was used. In operation, air was drawn through the instruments sampling tube by a high capacity blower, and droplets were collected by impaction on gelatin-coated slides. Development work on this technique (Jiusto, 1965 and Mack, 1966) has shown that there is approximately a 2:1 ratio between the diameter of the impaction crater formed in the gelatin and the diameter of the impinging droplet. The sampling airspeed ($\sim$50 m/s) was measured by a pitot tube and static source mounted in the unit, and a standard aircraft airspeed indicator was used to read the airspeed through the sampler. A 30 second exposure time was used to collect the in-smoke aerosol samples. Reduction of the droplet data was performed manually from photomicrographs of the sample slides obtained with a phase contrast microscope. The raw distributions produced from measurements of the droplet replicas were then corrected for the collection efficiency of the slide as a function of droplet diameter and air speed.

Due to the manual operation of the Drop Sampler and the relatively brief periods for which the ship was positioned in the smoke plumes, acquisition of samples was not always practical. Additionally, for the samples acquired, analysis for particles greater than 5 um diameter was hampered by an overwhelming abundance of smaller particles.

In recognition of the above sampling difficulties associated with the three aerosol sizing instruments, the data have been inspected accordingly and only those data which were free from apparent sampling errors have been reported.

The chemical composition of the smoke was determined via energy dispersive x-ray analysis in conjunction with scanning electron microscopy. Two sampling methods were employed to obtain samples for this analysis: the aforementioned filter samples and impactor samples, collected upon the third and fourth stages of a four stage Casella impactor.

With the exception of the second burn, each of the ten burns was video taped. Also, numerous still photographs of each burn were obtained, and, for burns 1 and 7, photographs were taken from aboard the Zodiac launch positioned approximately 1 km from the Lynch. Appendix C provide several photographs of the ship, instrumentation and smoke plumes.

Section 3

EXTINCTION CHARACTERISTICS OF THE CY85A OBSCURANT AEROSOL

During the cruise, ten 160 pound payloads of CY85A pyrotechnic were combusted. The date and time of each burn and the type of measurements performed by Calspan on the resultant smoke are summarized in Table 2. Note that burns No. 7 and 10 were conducted to obtain only photographic and lidar data, and, hence, no in-smoke measurements were made.

Nominal Mass Extinction Coefficient

For each burn (except Nos. 7 and 10), measurements of the smoke's scattering coefficient and mass loading were made. Plots of the scattering coefficient as a function of time for each of these burns are presented in Appendix A. Also shown on the plots are the sampling periods of the mass loading filters.

For times when simultaneous measurements of the smokes' scattering coefficient and mass loading were available, the corresponding nominal mass extinction coefficient was computed. Table 3 presents a summary of the scattering coefficients, mass loadings and calculated nominal mass extinction coefficients for each burn.

As can be seen from Table 2, measurements were made in both thin and dense smokes ranging in mass concentration from 46 to 13600 ug/m^3 and having scattering coefficients from approximately 0.2 to 33 km^{-1}. The values of the computed nominal mass extinction coefficient ranged from 1.77 to 3.67 m^2/g with an average of 2.60 m^2/g.

Size Distribution Measurements

As discussed earlier, three instruments were used to measure the aerosol size distributions in the smokes: A TSI EAA ($0.01 \leq D \leq 1.0$ um), a Royco OPC ($0.47 \leq D \leq 10$ um), and a large particle impaction device ($D \gtrsim 2$ um). Aerosol concentrations measured in the smokes relative to background levels can be seen from the size distribution plots presented in Figures 1, 2 and 3 for the EAA, Royco and Drop Sampler, respectively. For the EAA distributions of Figure 1, the corresponding Royco data have been added

Table 2

TEST LOG

TEST PARAMETERS			ACQUIRED DATA						
			SIZE DISTRIBUTION						
BURN NO.	DATE AND TIME OF IGNITION (GMT)	RH	EAA (.01-1)	ROYCO (.5-10)	D.S. (>2)	SCATTERING COEFFICIENT	MASS LOADING FILTER SAMPLE	IMPACTION SAMPLE	VIDEO TAPE
1	20 MARCH @ 1230	63%	X	X		(X)	X	X	X
2	20 MARCH @ 1338	65%	X	X		X	X	X	
3	20 MARCH @ 1625	65%			X	X	X	X	X
4	20 MARCH @ 1808	66%		X		(X)	X	X	X
5	23 MARCH @ 1533	74%		X		X	X	X	X
6	23 MARCH @ 1654	74%	X	X	X	X	X	X	X
7	23 MARCH @ 1750	74%	(PHOTOGRAPHIC DATA ONLY)						X
8	30 MARCH @ 1103	67%		X	X	X[1]	X	X	X
9	30 MARCH @ 1609	59%		X	X	X[1]	X	X	X
10	30 MARCH @ 1933	67%	(PHOTOGRAPHIC DATA ONLY)						X

( ): PARTIAL DATA
1: DATA OBTAINED FROM NRL'S HSS NEPHELOMETER

Table 3

SUMMARY OF NOMINAL MASS EXTINCTION COEFFICIENT COMPUTATIONS

BURN NO.	SAMPLE PERIOD (GMT)	SAMPLE NOMINAL MASS (mg)	NOMINAL MASS LOADING ($\mu g/m^3$)	AVERAGE SCAT. COEF. ($10^{-4} m^{-1}$)	COMPUTED NOMINAL MASS EXT. COEF. (m^2/g)
1	1308 - 1328	0.12	107	—	—
2	1426 - 1438	0.03	46	2.32	2.16
3	1656 - 1706	0.045	83	3.05	3.67
4	1813 - 1824	0.045	75	—	—
5	1540 - 1550	0.075	135	4.10	3.04
6	1707 - 1751	0.19	82	2.24	2.73
	1707 - 1731	0.13	100	2.52	2.52
	1732 - 1745	0.05	71	2.04	2.87
8	1104 - 1113	1.64	4290	(76.1)	(1.77)
9	1610.8 - 1614.6	1.57	10608	261	2.46
	1610.8 - 1613.2	1.47	13611	325	2.38
	1613.9 - 1614.4	0.12	4580	111	2.42

( ): Value based on limited data.

to provide a more complete size distribution for these four times. Appendix B presents the size distribution data in tabular form. For additional information on the smoke size distributions, reference should be made to concurrent measurements performed by NRL (Hoppel and Frick, 1983).

Perhaps the most significant conclusion to be drawn from these measurements is the apparent initial presence of large particles (diameter $\gtrsim$3 um) which then experience rapid fallout. For burns 1 through 6, in-plume measurements were obtained in relatively thin smokes and often 20 to 50 minutes after dissemination. In these tests, few large particles were observed above the natural background concentrations. On the other hand, in burns 8 and 9, measurements were made in dense smokes within minutes of aerosolization. In these latter tests, significant numbers of large particles were observed as indicated in Figures 2 and 3. For a brief period during test 9, the wind blew smoke from the burning pyrotechnic directly back onto the ship. Those people exposed to the smoke during this period reported feeling a fine fallout settling on their skin and, after the burn, the fallout was visibly evident upon exposed horizontal surfaces. It was also the personal opinion of several of the scientists on board that shortly after aerosolization in most burns, areas of general aerosol fallout could be detected in the smoke clouds. While no size measurements were made on the fallout particles, our first-guess estimate would place their diameter at >50 um.

Thus, it appears that immediately following aerosolization, large particles were present in the smokes and that the largest of these particles were lost via sedimentation within a few minutes. In all of the plumes observed, particle concentrations at sizes $\gtrsim$3 um diameter returned to background levels within a period of 30 to 60 minutes.

Chemical Composition of the Obscurant Smoke

A mass loading filter sample from burn 9 which was densely coated with smoke aerosol was subjected to energy dispersive x-ray analysis for determination of the smoke's elemental composition. A relatively large area of the filter was scanned thereby encompassing literally thousands of smoke aerosol particles. Figure 4 presents the resultant composite spectrum and indicates, as expected, that the primary elemental constituents of the smoke were chlorine and potassium.

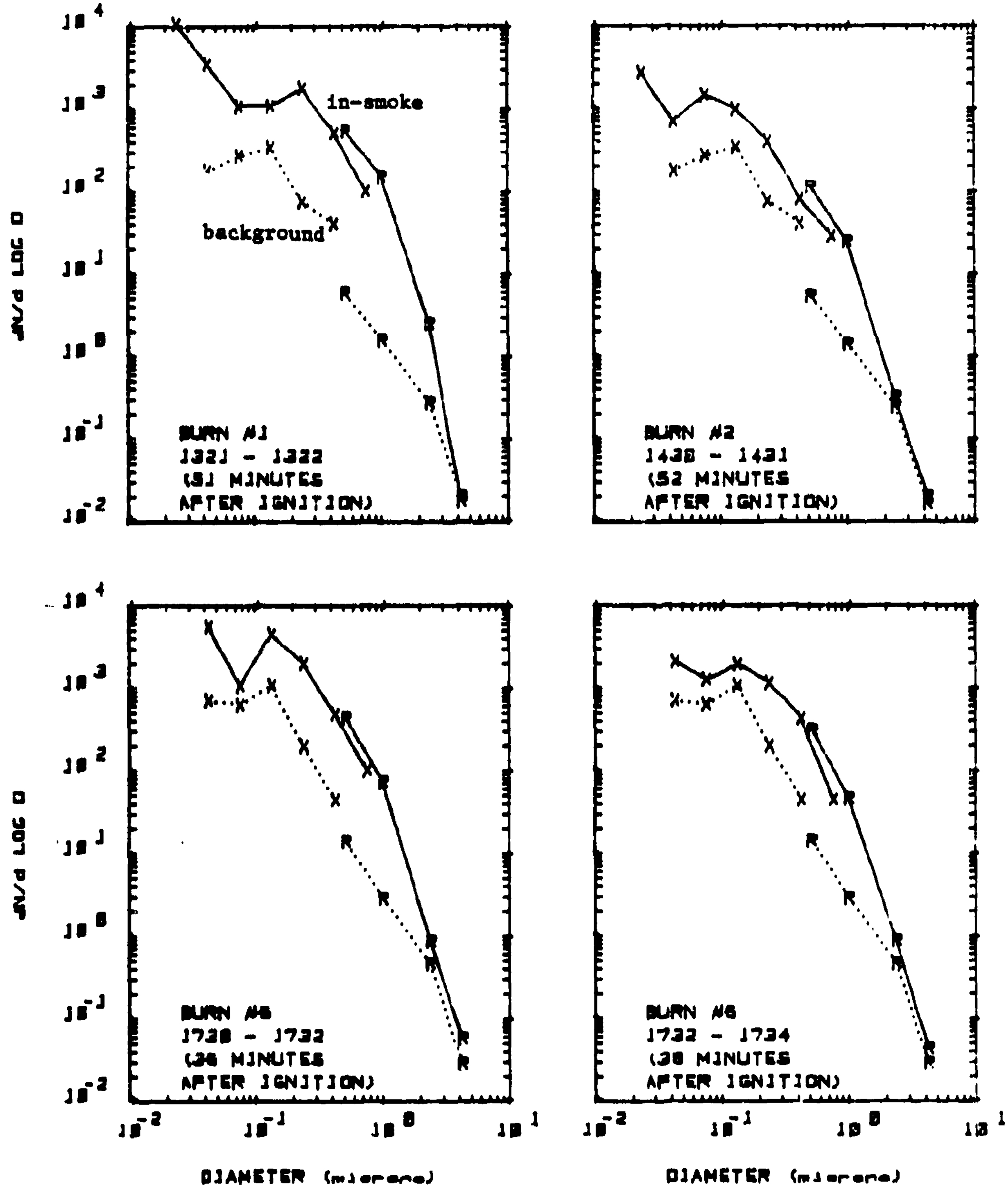

Figure 1. EAA (X's) aerosol size distributions (0.01 - 1.0 µm diameter) of CY85A smoke. Corresponding Royco (R's) data (0.47 - 10 µm diameter) also shown. Dotted line represents background conditions.

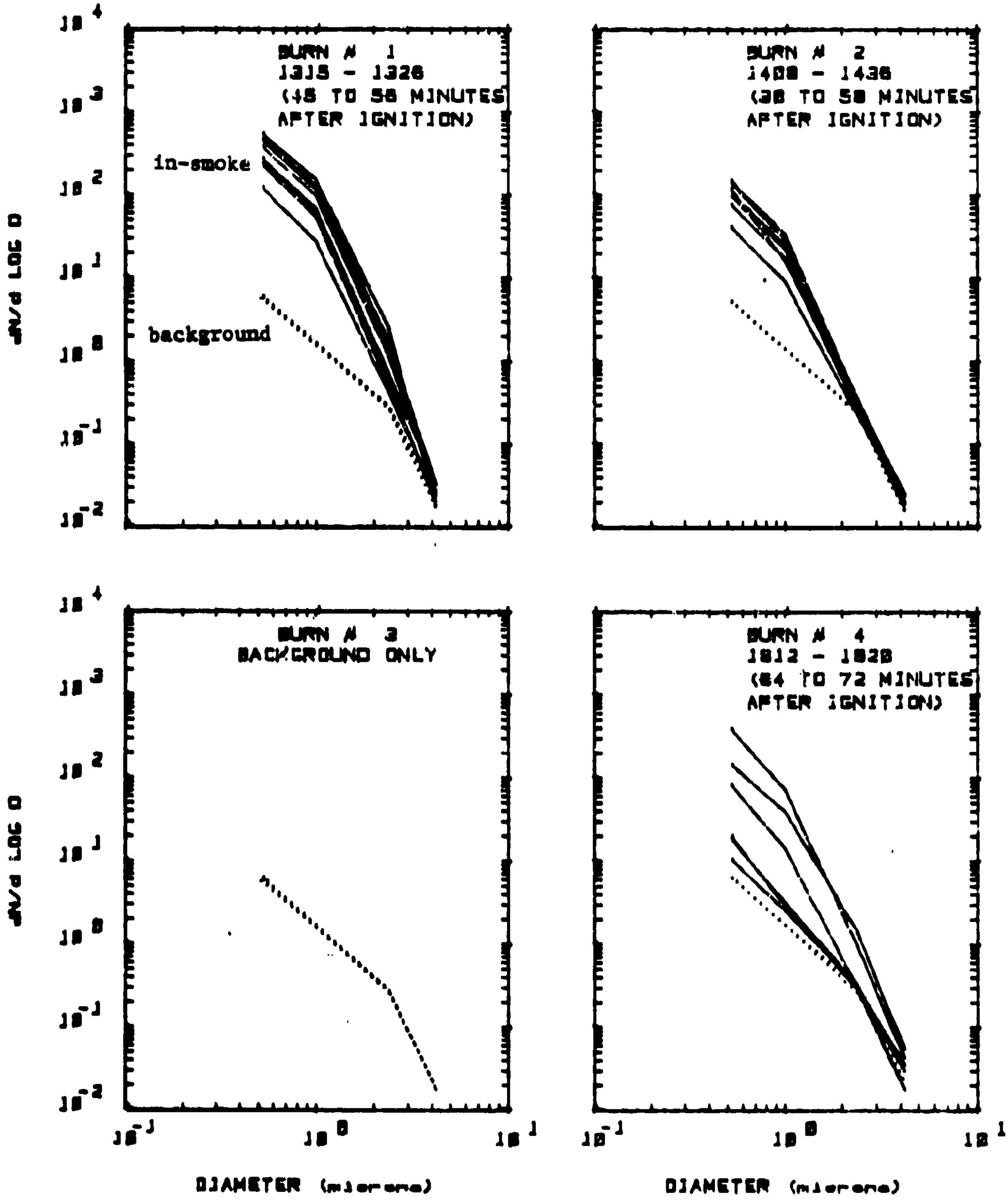

Figure 2. Royco aerosol size distributions (0.47 - 10 μm diameter) of CY85A smoke. Dotted line represents background condition.

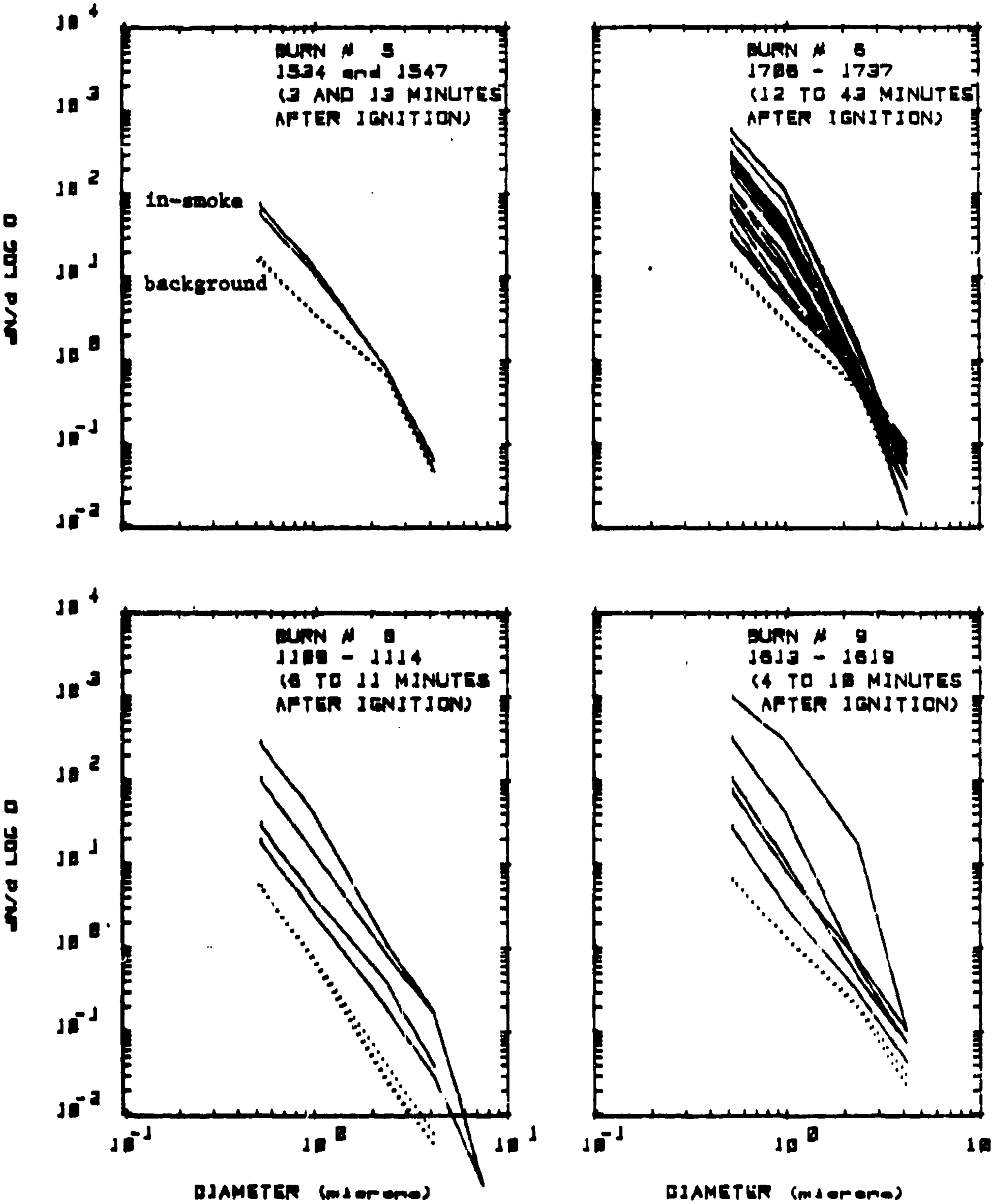

Figure 2. Continued.

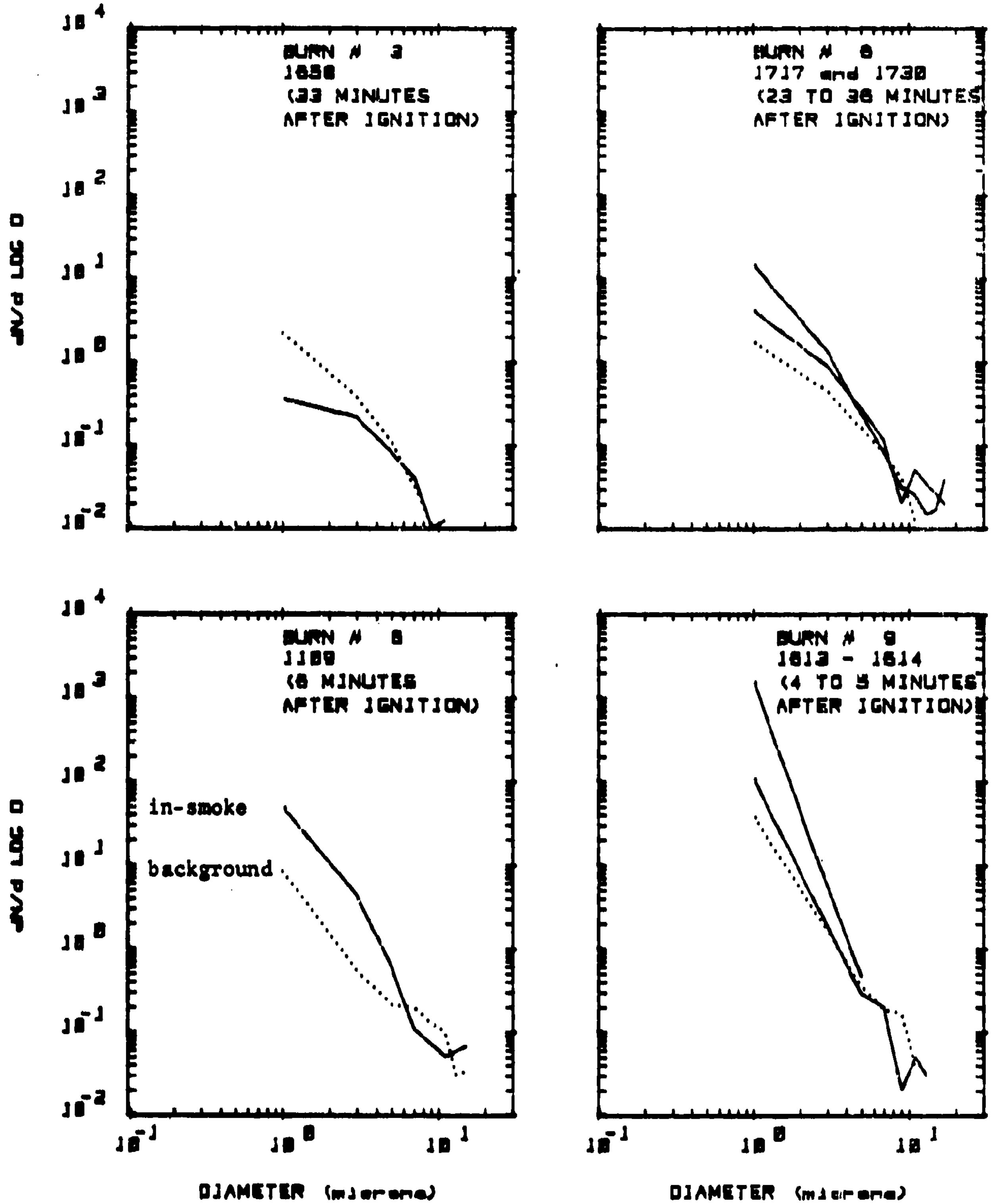

Figure 3. Drop Sampler size distributions (>1 µm diameter) of CY85A smoke. Dotted line represents background condition.

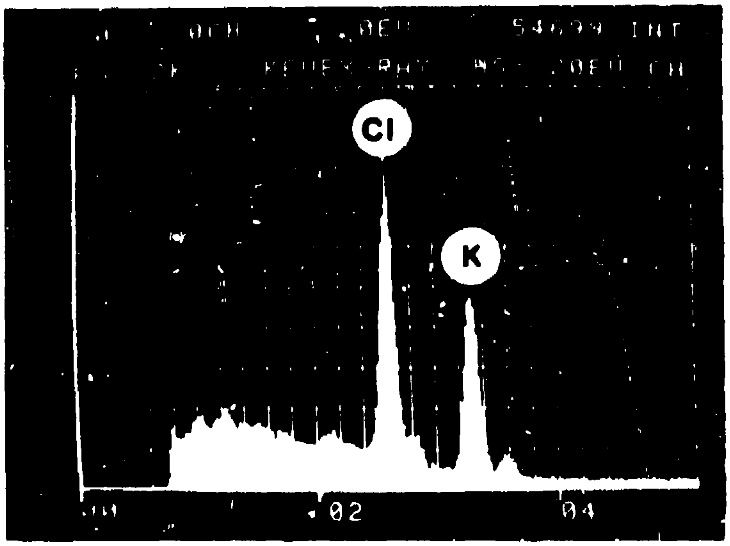

Figure 4. SEM energy dispersive X-ray spectrum of CY85A smoke sample (at-sea Test No. 9. 30 March 1983).

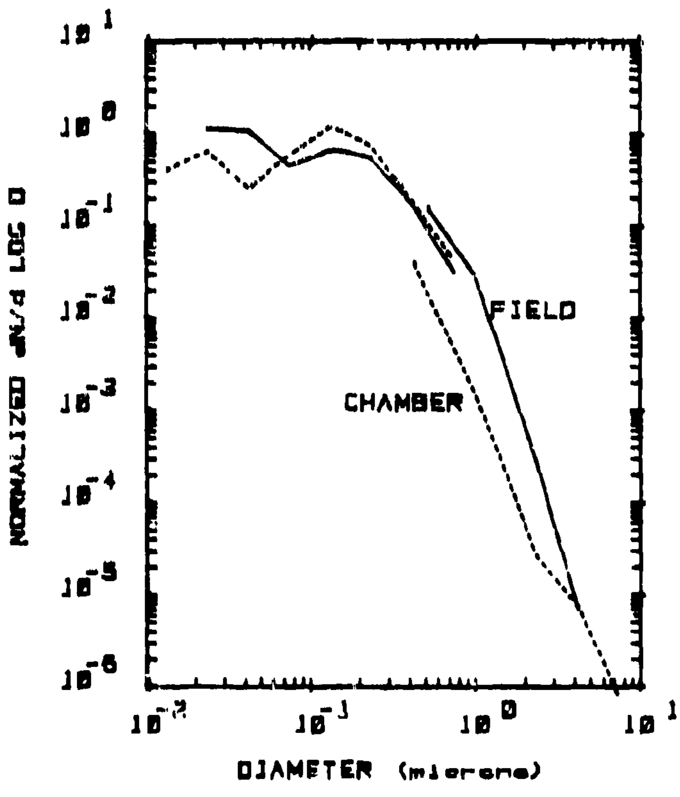

Figure 5. Comparison of chamber and field size distribution measurements of CY85A smoke (background aerosol factored out).

Comparison of Field and Chamber Measurements

The at-sea trial of the CY85A pyrotechnic provided data for comparison to similar measurements obtained during tests of the pyrotechnic in Calspan's 600 m^3 chamber over the past five years (References 1-5).

Measurement of the nominal mass extinction coefficient in the chamber for tests conducted at humidities $\leq$ 75% RH (to be consistent with humidities occurring during the at-sea field tests) have ranged from 2.16 to 4.63 m^2/g. Thus, the field measurements, which ranged from 1.77 to 3.67 m^2/g (Table 2), are in reasonable agreement with the chamber results.

Size distribution measurements from chamber tests (Hanley et al 1983, average of tests 1 and 2) were also in general agreement with the field measurements as shown in Figure 5. For this comparison, background aerosol have been factored out, and the distributions have been normalized by the total smoke aerosol number concentration. It must be noted, however, that this comparison is based on very limited field data obtained only in low concentration smokes for which the EAA was not overloaded. Additionally, these particular field measurements were made from 35 to 50 minutes after aerosolization and significant loss of large particles by sedimentation likely occurred.

Chemical analyses of aerosol samples from both the field and chamber tests indicate that the CY85A smoke is primarily KCl (See Figure 4 and Reference 5).

Section 4
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The CY85A smoke, being primarily KCl, requires a relative humidity of approximately 80% for complete deliquescence to occur. Relative humidities encountered during the cruise were most often less than 80% (Wattle et al, 1983) and during the smoke tests ranged from 59% to 74%. Thus, the at-sea trial was performed on an essentially dry CY85A smoke, and additional obscuration due to hygroscopic growth was minimal.

The principal conclusions drawn from this year's at-sea field trial are:

1. The visible wavelength nominal mass extinction coefficient of the smokes ranged from 1.77 to 3.67 with an average of 2.60 m^2/g.

2. Observations and size distribution measurements suggest that upon aerosolization large ($\gtrsim$3 um) particles were present in the smokes in significant concentrations but that these concentrations were significantly reduced by sedimentation over periods from 30-60 minutes. The largest particles, i.e., $\gtrsim$50 um, precipitated from the smoke within minutes.

3. A limited comparison showed that the extinction, size distribution and chemical composition measurements made during the at-sea trial are consistent with results from previous chamber tests.

4. The chemical composition of the CY85A smoke is primarily KCl.

5. Relative humidities encountered during the cruise were generally below the deliquescence threshold of the CY85A ($\sim$80% RH).

Recommendations

In these at-sea trials, the 160 pound payload pyrotechnics apparently produced considerable quantities of very large particles (estimated to be greater than ~50um in diameter) which fell out of the smoke screen almost immediately. Except for an expected short-term (i.e., less than several minutes) increase in obscuration immediately after combustion, these very large particles represent an inefficiency in the smoke production process. It is recommended that study to optimize the combustion-aerosolization process be undertaken.

During the past few years, NWC has been developing alternate formulations of the CY85A pyrotechnic directed towards lowering the smoke's deliquescence humidity. As a result of this effort, smoke formulations, which deliquesce at 13 and 33% RH (pyrotechnic LM9 and LM12 respectively) have been produced in small quantities, and evaluated in Calspan's chamber. In addition to offering a lower deliquescence threshold, these smokes also provide greater extinction than CY85A at both visible (LM9) and IR (LM12) wavelengths as seen in Figure 6. Based on last year's work (Hanley et al, 1983) with the LM9, LM11 and LM12 pyrotechnics, the following selected conclusions are restated from that study:

- Low humidity IR wavelength (3-12 um) obscuration provided by the LM11 and LM12 pyrotechnics is up to 40 times the obscuration provided by CY85A, and, at high humidity, up to 10 times greater than CY85A.

- Based on payload mass, LM9 provides approximately three times the obscuration of CY85A at low humidity over nearly all wavelengths measured (0.5-14 um). At high humidity, the obscuration provided by LM9 and CY85A is nearly equivalent.

Thus, in light of the relatively low humidities (i.e., < 80% RH) encountered during the at-sea trial and the potential for significantly increased extinction, it is recommended that development continue on these low deliquescent humidity smokes as an improvement on the present CY85A pyrotechnic.

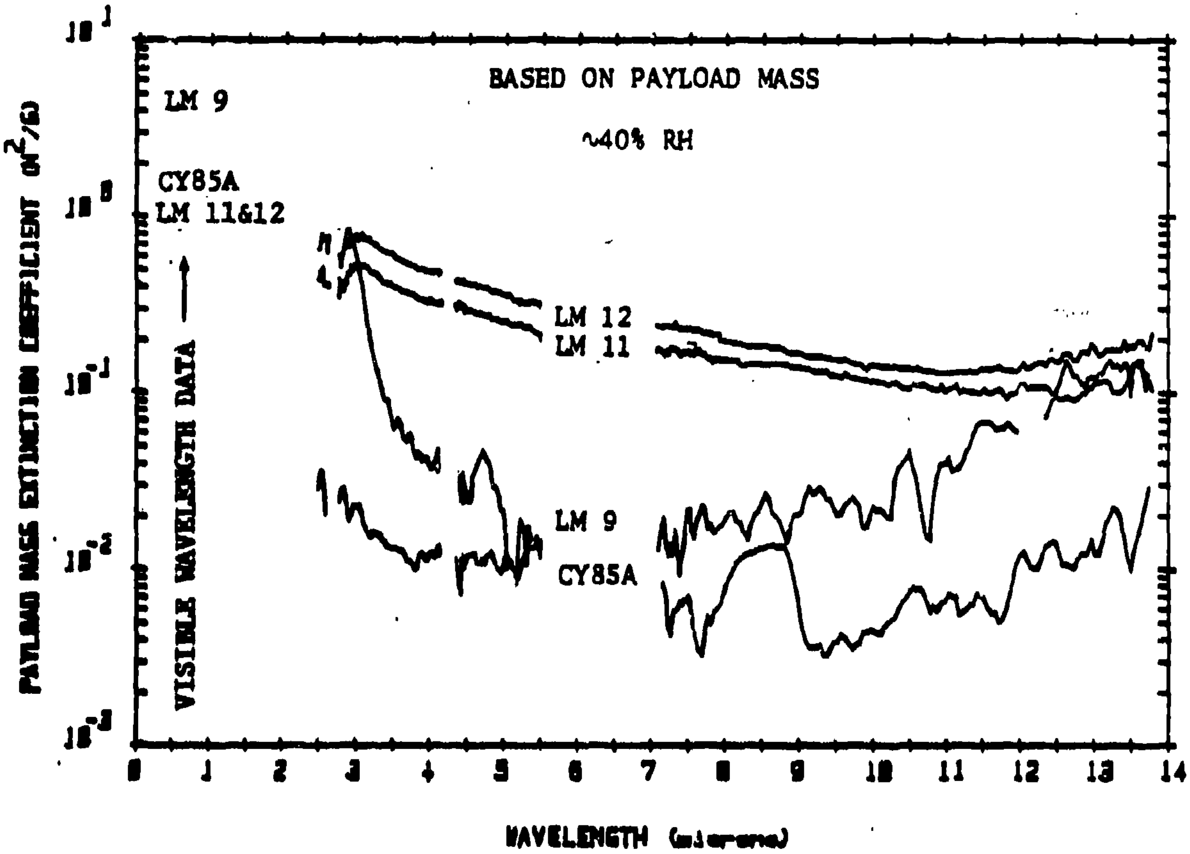

Figure 6. A comparison of the extinction per unit payload mass of several NWC pyrotechnics based on chamber tests conducted at ~40% RH (Hanley et al, 1983).

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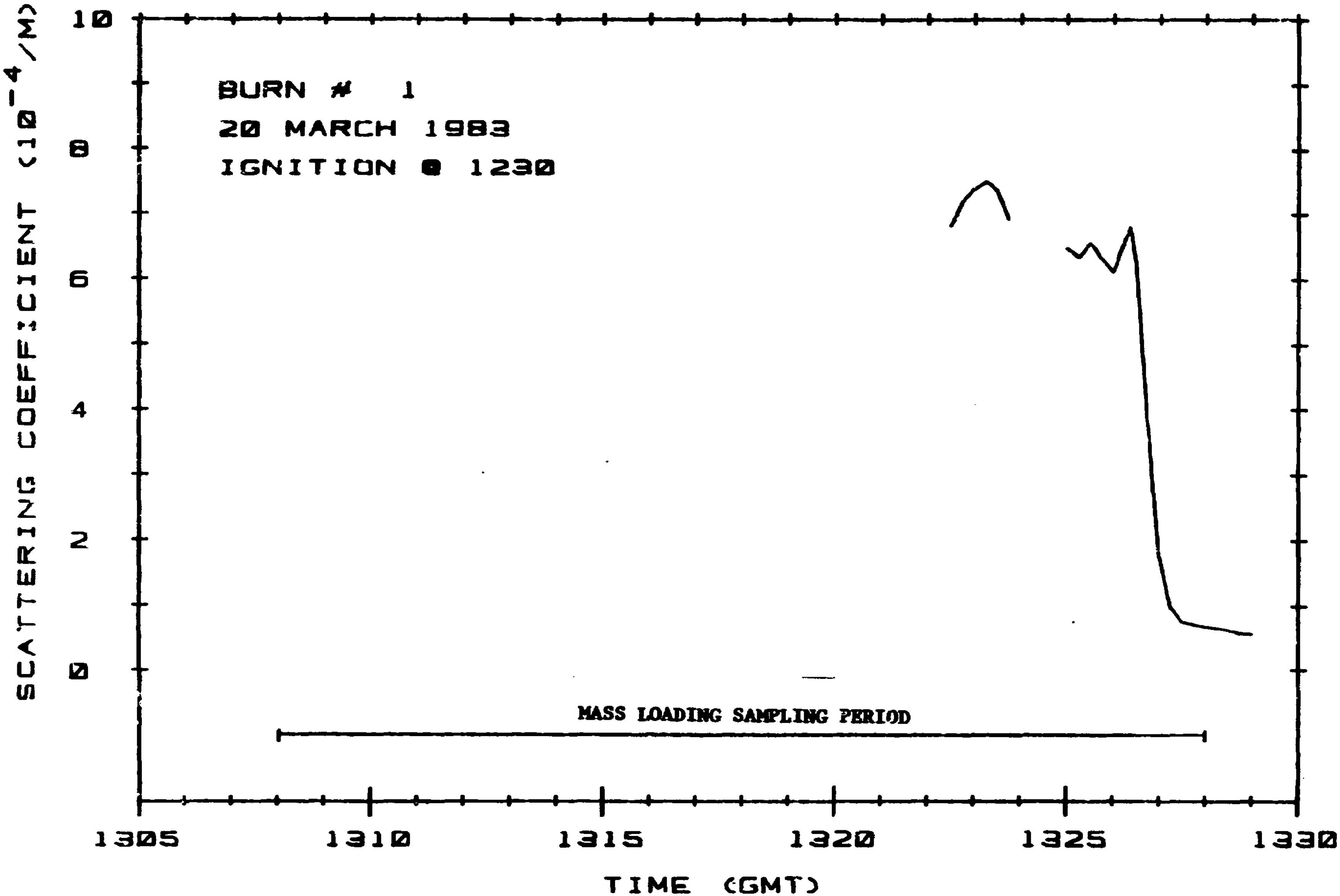
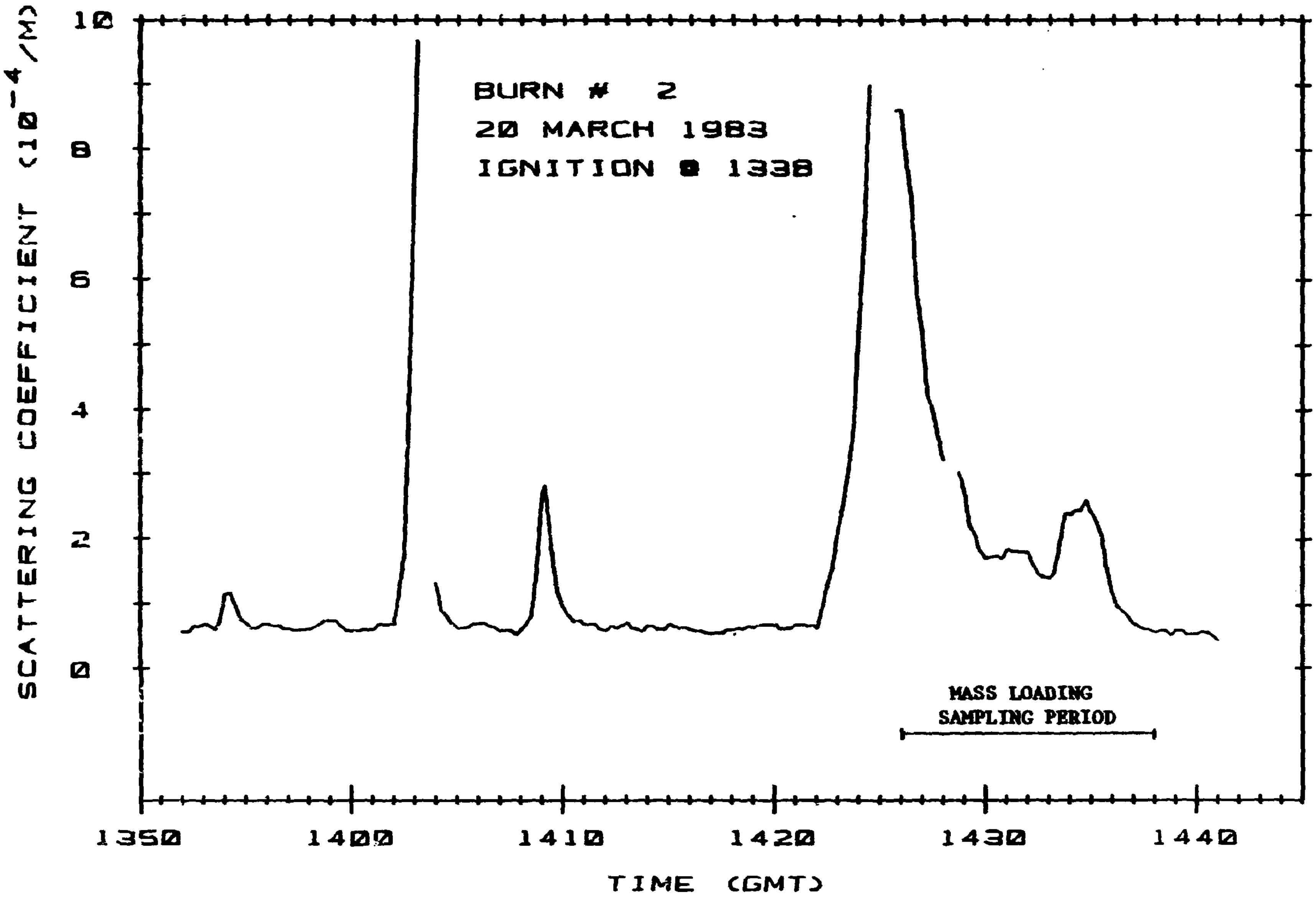
APPENDIX A

Scattering coefficient as a function of time and mass loading filter sampling periods for the CY85A pyrotechnic burns.


SCATTERING COEFFICIENT (10^-4/M)
10
8
6
4
2
0
BURN # 1
20 MARCH 1983
IGNITION @ 1230
MASS LOADING SAMPLING PERIOD
1305
1310
1315
1320
1325
1330
TIME (GMT)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6
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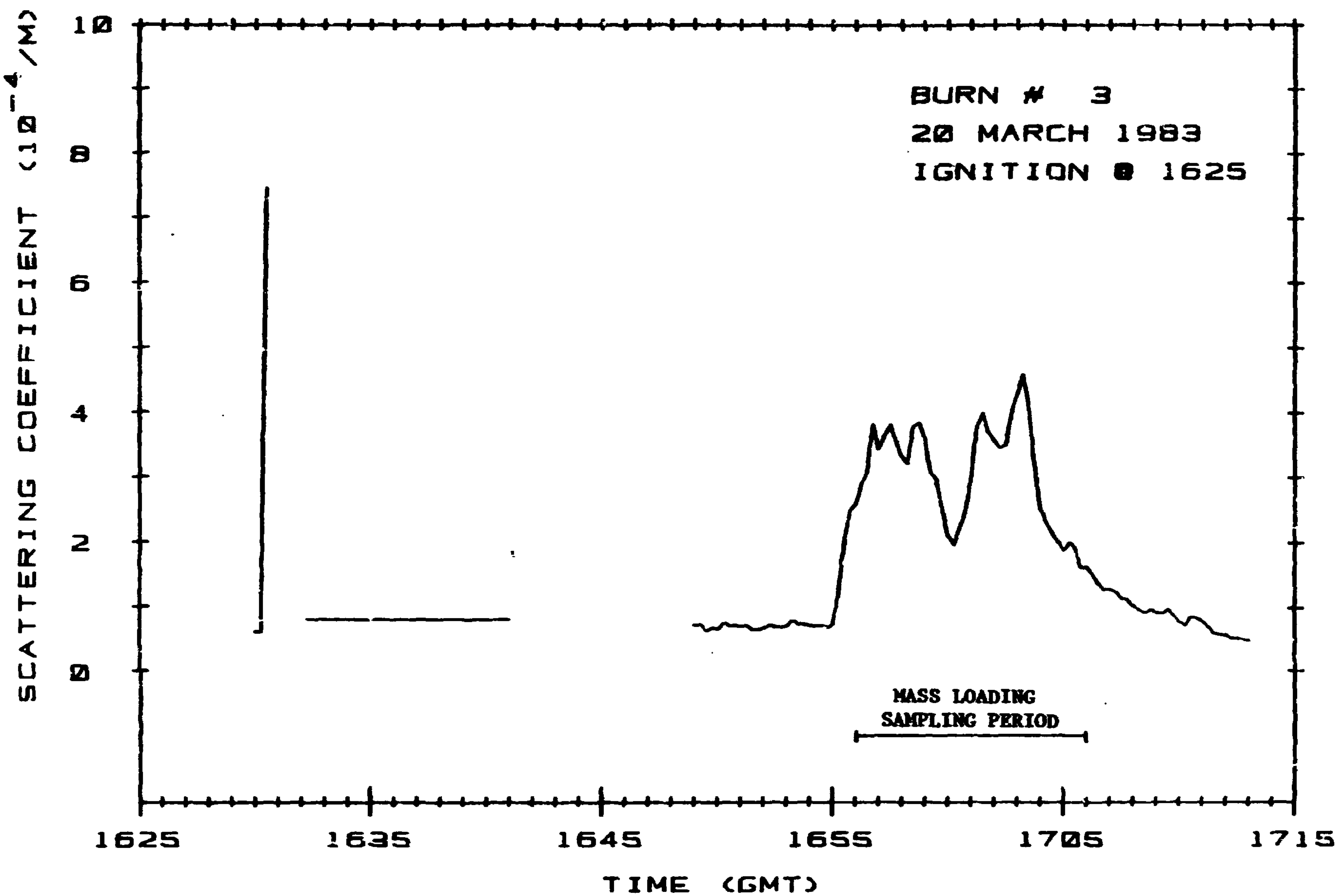
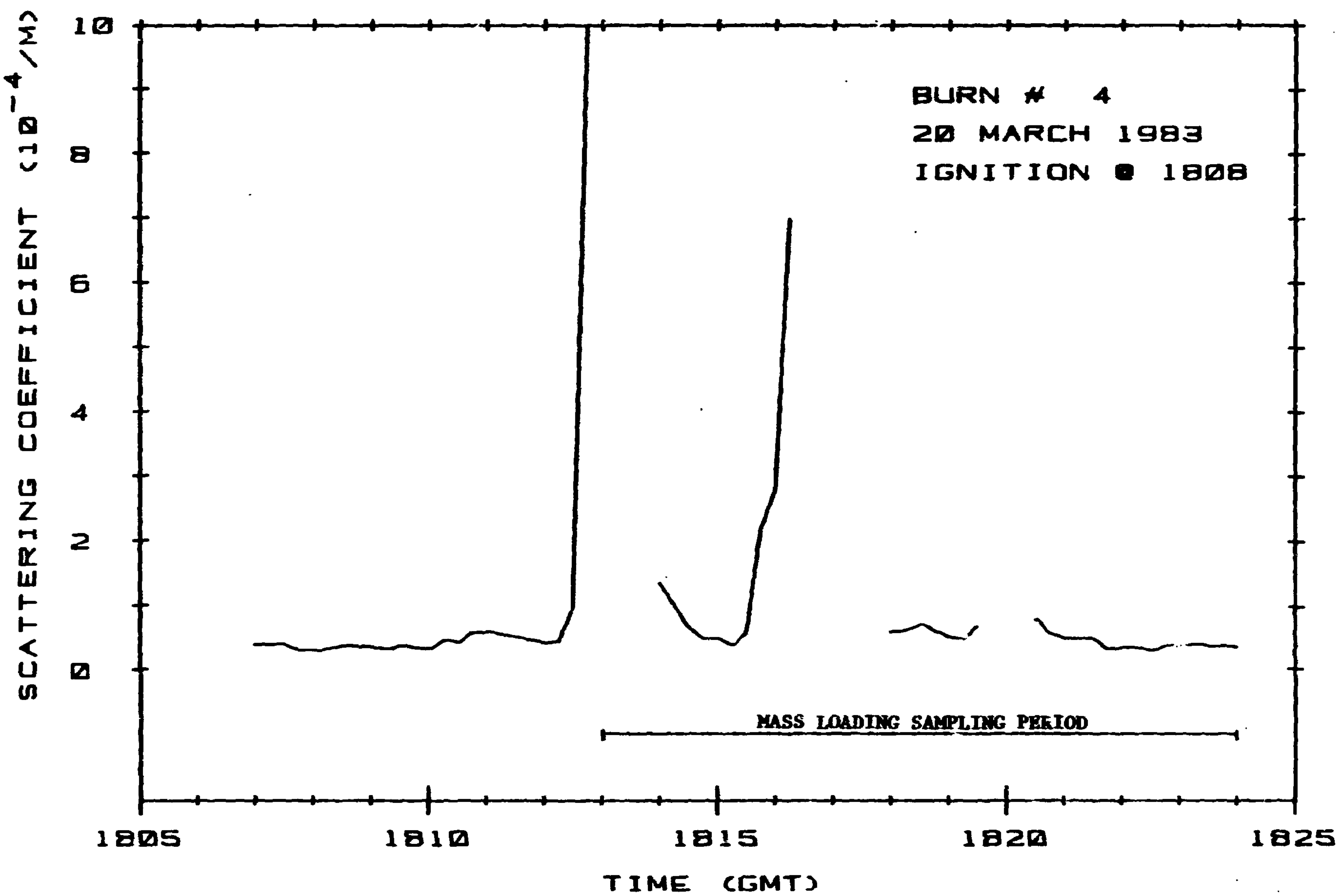
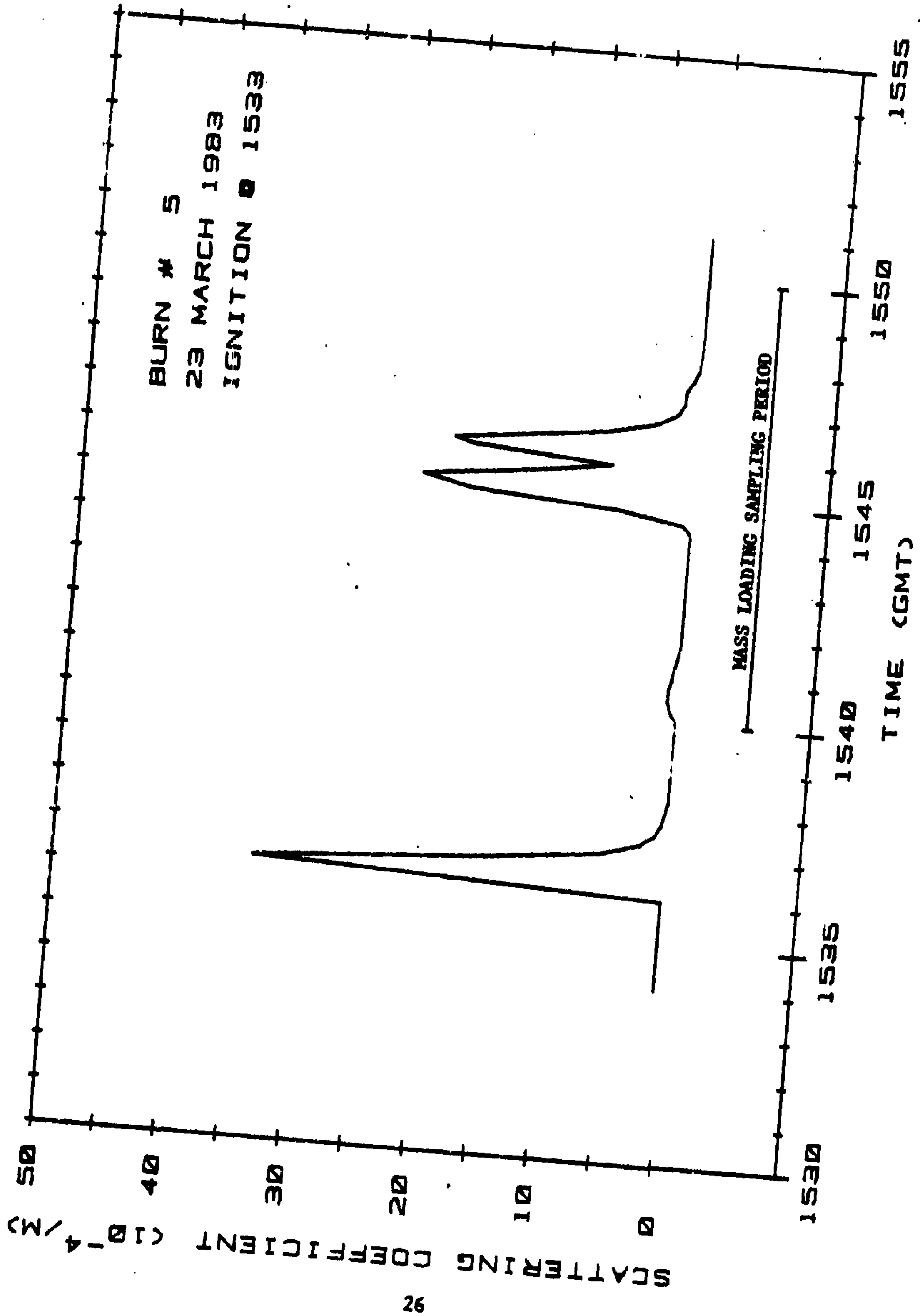
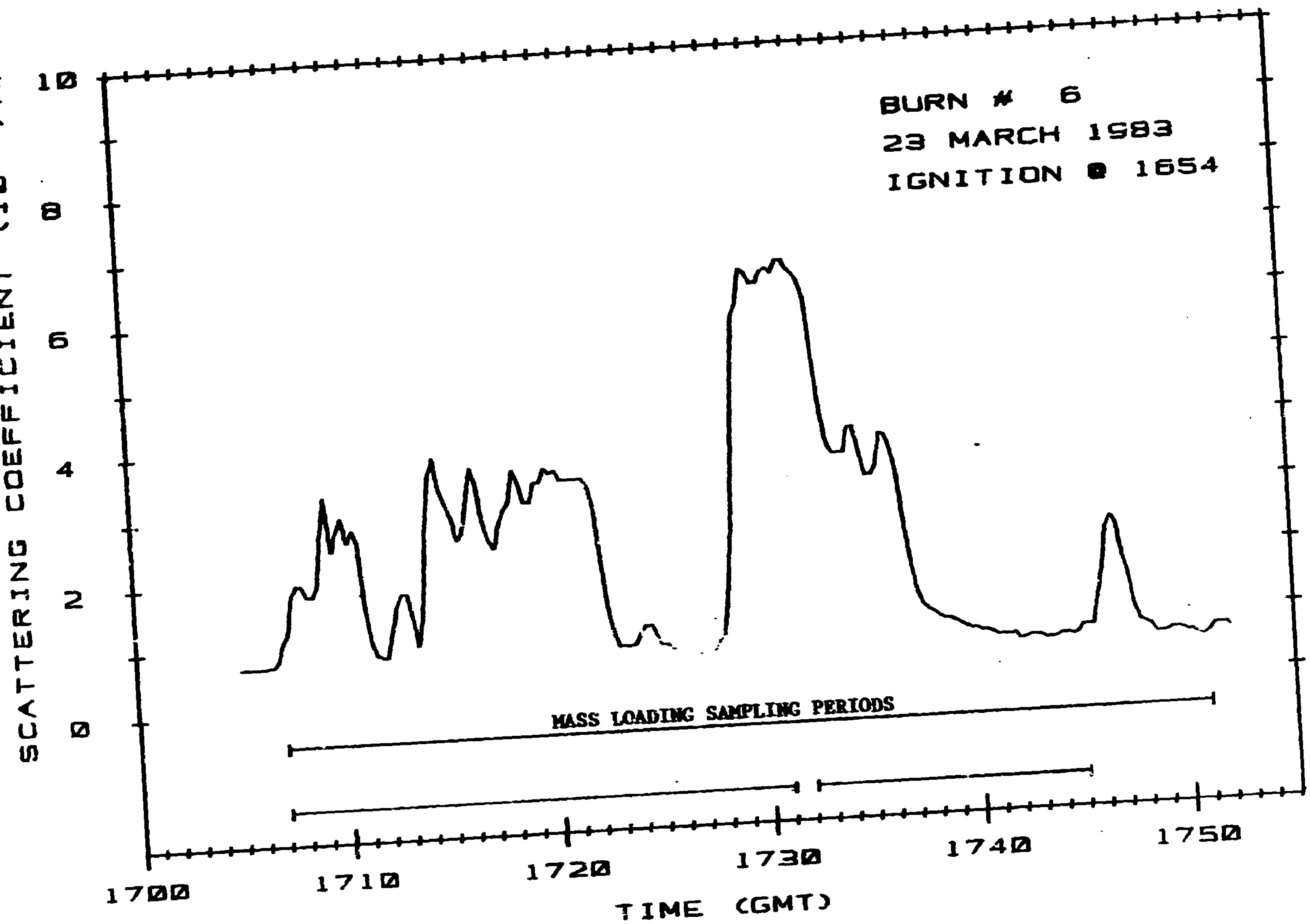
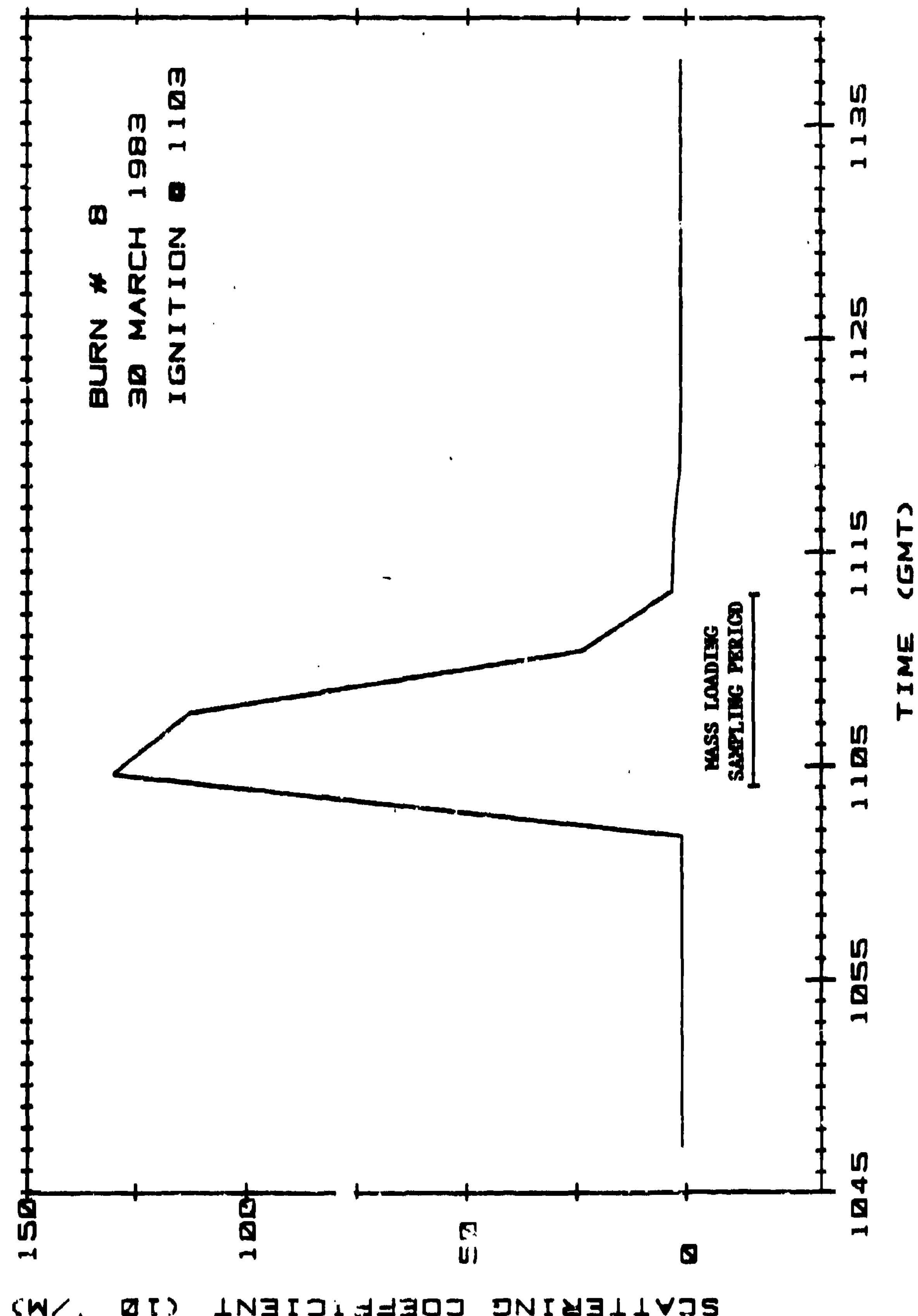
1430
1440
TIME (GMT)
MASS LOADING
SAMPLING PERIOD

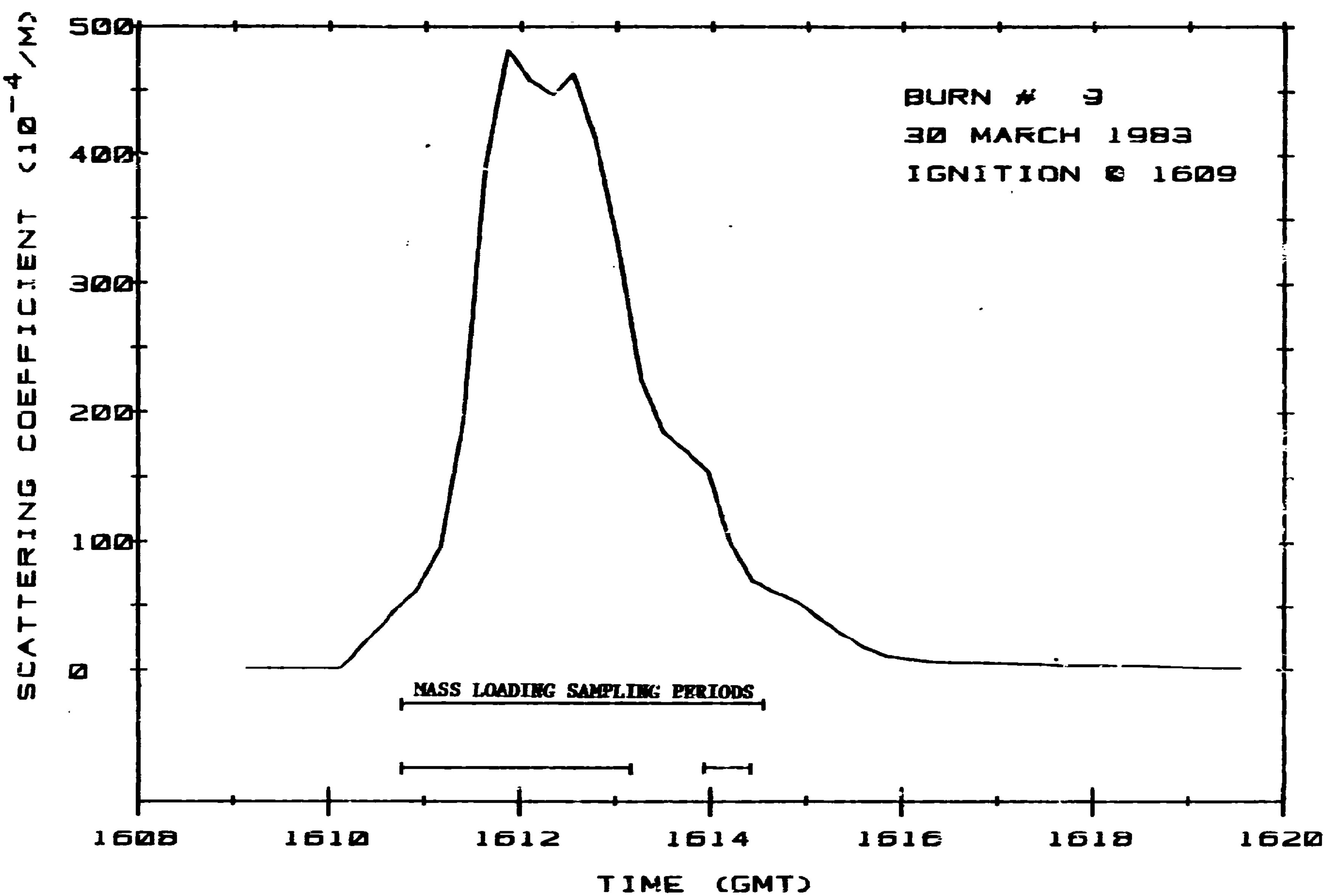

BURN # 3
20 MARCH 1983
IGNITION @ 1625
MASS LOADING
SAMPLING PERIOD
SCATTERING COEFFICIENT (10^-4/M)
10
8
6
4
2
0
1625
1635
1645
1655
1705
1715
TIME (GMT)


BURN # 4
20 MARCH 1983
IGNITION @ 1808
MASS LOADING SAMPLING PERIOD
10
8
6
4
2
0
SCATTERING COEFFICIENT (10^-4/M)
1805
1810
1815
1820
1825
TIME (GMT)


BURN # 5
23 MARCH 1983
IGNITION @ 1533
MASS LOADING SAMPLING PERIOD
SCATTERING COEFFICIENT (10^-4/M)
50
40
30
20
10
0
1530
1535
1540
1545
1550
1555
TIME (GMT)


BURN # 6
23 MARCH 1983
IGNITION @ 1654
MASS LOADING SAMPLING PERIODS
SCATTERING COEFFICIENT (10^{-4}/M)
10
8
6
4
2
0
1700
1710
1720
1730
1740
1750
TIME (GMT)


BURN # 8
30 MARCH 1983
IGNITION @ 1103
MASS LOADING
SAMPLING PERIOD
1045
1055
1105
1115
1125
1135
TIME (GMT)
150
100
50
0
SCATTERING COEFFICIENT (10^{-4}/M)


BURN # 3
30 MARCH 1983
IGNITION @ 1609
MASS LOADING SAMPLING PERIODS
SCATTERING COEFFICIENT (10^-4/M)
0
100
200
300
400
500
1608
1610
1612
1614
1616
1618
1620
TIME (GMT)

APPENDIX B

Tabulated size distributions and sample times for the EAA, Royco and Drop Sampler aerosol analyzers.

EAA DATA

BURN # 1

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) .0100 - .0178	.0178 - .0316	.0316 - .0562	.0562 - .1000	.100 - .178	.178 - .316	.316 - .562	.562 - 1.000
1213 - 1214	BACKGROUND	0	0	0	89	48	25	13	0
1223 - 1224	BACKGROUND	0	0	87	44	120	12	7	0
1322 - 1323		0	2672	870	266	265	443	127	25

BURN # 2

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) .0100 - .0178	.0178 - .0316	.0316 - .0562	.0562 - .1000	.100 - .178	.178 - .316	.316 - .562	.562 - 1.000
1430 - 1431		0	668	174	355	241	98	20	7

BURN # 6

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) .0100 - .0178	.0178 - .0316	.0316 - .0562	.0562 - .1000	.100 - .178	.178 - .316	.316 - .562	.562 - 1.000
1650 - 1651	BACKGROUND	0	0	174	99	265	49	13	0
1652 - 1653	BACKGROUND	0	0	174	133	241	62	7	0
1655 - 1656	BACKGROUND	0	0	174	89	289	37	13	0
1731 - 1732		0	0	1392	266	1108	492	120	25
1733 - 1734		0	0	522	311	482	283	107	11

ROYCO DATA

BURN # 1

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1107 - 1117	BACKGROUND	4.28E-01	7.41E-01	6.48E-02	4.06E-03	0.00E 00
1117 - 1127	BACKGROUND	4.37E-01	7.77E-01	6.99E-02	5.19E-03	0.00E 00
1127 - 1137	BACKGROUND	4.64E-01	8.09E-01	6.85E-02	5.90E-03	0.00E 00
1315 - 1316		9.35E 00	1.33E 01	1.01E-01	6.00E-03	0.00E 00
1316 - 1317		1.77E 01	2.59E 01	1.25E-01	4.94E-03	0.00E 00
1317 - 1319		2.00E 01	2.95E 01	1.47E-01	4.24E-03	0.00E 00
1319 - 1320		2.10E 01	3.27E 01	1.71E-01	8.12E-03	0.00E 00
1320 - 1321		2.90E 01	4.71E 01	2.79E-01	6.36E-03	0.00E 00
1321 - 1322		4.10E 01	7.42E 01	6.15E-01	4.24E-03	0.00E 00
1323 - 1324		3.73E 01	6.25E 01	4.21E-01	7.77E-03	0.00E 00
1324 - 1325		3.48E 01	5.58E 01	3.31E-01	5.65E-03	0.00E 00
1325 - 1326		3.47E 01	5.68E 01	3.62E-01	6.00E-03	0.00E 00

BURN # 2

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1408 - 1409		9.29E 00	7.73E 00	3.65E-02	6.00E-03	0.00E 00
1428 - 1429		1.06E 01	1.41E 01	7.35E-02	4.59E-03	0.00E 00
1429 - 1430		7.41E 00	1.08E 01	7.63E-02	3.88E-03	0.00E 00
1430 - 1431		8.41E 00	1.21E 01	7.84E-02	4.94E-03	0.00E 00
1432 - 1433		5.87E 00	8.40E 00	6.60E-02	4.94E-03	0.00E 00
1433 - 1434		1.10E 01	1.60E 01	8.86E-02	5.65E-03	0.00E 00
1434 - 1435		1.15E 01	1.65E 01	8.65E-02	4.59E-03	0.00E 00
1435 - 1436		3.14E 00	4.46E 00	5.62E-02	4.94E-03	0.00E 00
1439 - 1449	BACKGROUND	4.01E-01	6.85E-01	6.06E-02	4.41E-03	0.00E 00
1449 - 1459	BACKGROUND	4.05E-01	6.90E-01	6.16E-02	3.60E-03	0.00E 00
1459 - 1509	BACKGROUND	4.05E-01	6.93E-01	5.93E-02	4.34E-03	0.00E 00

BURN # 3

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1549 - 1559	BACKGROUND	4.33E-01	7.62E-01	6.74E-02	4.27E-03	0.00E 00
1608 - 1618	BACKGROUND	4.54E-01	7.60E-01	6.40E-02	4.52E-03	0.00E 00
1619 - 1629	BACKGROUND	4.87E-01	8.12E-01	6.83E-02	4.31E-03	0.00E 00

BURN # 4

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1806 - 1807	BACKGROUND	4.93E-01	8.27E-01	7.80E-02	6.71E-03	0.00E 00
1807 - 1808	BACKGROUND	4.84E-01	8.30E-01	6.50E-02	5.30E-03	0.00E 00
1813 - 1814		1.09E 01	1.88E 01	3.52E-01	1.31E-02	0.00E 00
1814 - 1815		7.94E-01	1.22E 00	7.77E-02	8.48E-03	0.00E 00
1815 - 1816		6.28E 00	6.82E 00	7.49E-02	7.06E-03	0.00E 00
1816 - 1817		2.93E 01	3.47E 01	2.39E-01	1.02E-02	0.00E 00
1818 - 1819		1.51E 00	1.38E 00	7.03E-02	4.24E-03	0.00E 00
1820 - 1821		1.41E 00	1.52E 00	7.91E-02	4.24E-03	0.00E 00

BURN # 5

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1531 - 1532	BACKGROUND	1.21E 00	1.82E 00	1.69E-01	1.13E-02	0.00E 00
1532 - 1533	BACKGROUND	1.27E 00	1.82E 00	1.62E-01	1.02E-02	0.00E 00
1534 - 1535	BACKGROUND	1.31E 00	1.79E 00	1.84E-01	1.02E-02	0.00E 00
1536 - 1537		4.57E 00	5.87E 00	1.98E-01	1.52E-02	0.00E 00
1546 - 1547		5.72E 00	6.65E 00	1.92E-01	1.13E-02	0.00E 00

BURN # 6

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1651 - 1652	BACKGROUND	1.03E 00	1.35E 00	1.20E-01	1.06E-02	0.00E 00
1652 - 1653	BACKGROUND	1.12E 00	1.44E 00	1.06E-01	7.06E-03	0.00E 00
1653 - 1654	BACKGROUND	1.03E 00	1.43E 00	1.17E-01	3.53E-03	0.00E 00
1706 - 1707		5.06E 00	3.23E 00	1.77E-01	2.47E-02	0.00E 00
1708 - 1709		7.09E 00	4.86E 00	1.55E-01	3.53E-03	0.00E 00
1709 - 1710		9.05E 00	6.72E 00	1.31E-01	1.41E-02	0.00E 00
1710 - 1711		3.52E 00	2.53E 00	1.48E-01	7.06E-03	0.00E 00
1711 - 1712		8.07E 00	5.54E 00	1.09E-01	0.00E 00	0.00E 00
1712 - 1713		5.54E 00	4.98E 00	1.13E-01	7.06E-03	0.00E 00
1713 - 1714		2.24E 01	2.15E 01	1.91E-01	7.06E-03	0.00E 00
1714 - 1715		1.69E 01	1.54E 01	1.91E-01	1.06E-02	0.00E 00
1716 - 1717		1.41E 01	1.31E 01	1.66E-01	1.77E-02	0.00E 00
1717 - 1718		1.71E 01	1.54E 01	1.84E-01	1.06E-02	0.00E 00
1718 - 1719		1.81E 01	1.61E 01	1.52E-01	3.53E-03	0.00E 00
1719 - 1720		1.99E 01	1.71E 01	1.31E-01	1.41E-02	0.00E 00
1720 - 1721		2.08E 01	2.01E 01	2.30E-01	3.53E-03	0.00E 00

ROYCO DATA (CONTINUED)

BURN # 6 (CONTINUED)

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1722 - 1723		2.49E 00	2.72E 00	1.77E-01	7.06E-03	0.00E 00
1723 - 1724		2.23E 00	2.43E 00	1.59E-01	1.77E-02	0.00E 00
1727 - 1728		9.37E 00	8.78E 00	1.34E-01	7.06E-03	0.00E 00
1728 - 1729		4.46E 01	5.36E 01	3.04E-01	1.41E-02	0.00E 00
1729 - 1730		4.42E 01	5.45E 01	4.03E-01	1.06E-02	0.00E 00
1730 - 1731		4.35E 01	5.16E 01	3.28E-01	1.06E-02	0.00E 00
1731 - 1732		3.31E 01	3.63E 01	2.12E-01	1.41E-02	0.00E 00
1733 - 1734		2.31E 01	2.29E 01	2.15E-01	1.06E-02	0.00E 00
1734 - 1735		2.07E 01	2.09E 01	1.91E-01	1.06E-02	0.00E 00
1735 - 1736		2.32E 01	2.26E 01	2.08E-01	1.06E-02	0.00E 00
1736 - 1737		6.13E 00	5.64E 00	1.48E-01	7.06E-03	0.00E 00

BURN # 8

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1047 - 1048	BACKGROUND	4.31E-01	3.34E-01	6.00E-03	1.06E-03	0.00E 00
1048 - 1049	BACKGROUND	4.25E-01	3.71E-01	9.89E-03	1.41E-03	0.00E 00
1049 - 1050	BACKGROUND	4.24E-01	3.74E-01	6.71E-03	1.06E-03	0.00E 00
1110 - 1111		2.16E 01	1.96E 01	2.73E-01	4.03E-02	0.00E 00
1111 - 1112		7.97E 00	6.71E 00	2.03E-01	3.89E-02	3.53E-04
1112 - 1113		2.35E 00	2.00E 00	9.46E-02	9.18E-03	0.00E 00
1113 - 1114		1.46E 00	1.25E 00	4.66E-02	8.71E-03	3.53E-04

BURN # 9

SAMPLE TIME (GMT)	SAMPLE	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0.47-0.56	0.56-1.78	1.78-3.16	3.16-5.62	5.62-10
1523 - 1533	BACKGROUND	5.01E-01	6.63E-01	4.99E-02	7.31E-03	0.00E 00
1533 - 1543	BACKGROUND	5.15E-01	6.39E-01	4.56E-02	5.40E-03	0.00E 00
1613 - 1614		7.45E 01	1.39E 02	4.15E 00	2.47E-02	0.00E 00
1614 - 1615		2.44E 01	1.92E 01	1.45E-01	1.77E-02	0.00E 00
1616 - 1617		8.11E 00	5.21E 00	1.06E-01	1.77E-02	0.00E 00
1617 - 1618		5.77E 00	4.04E 00	1.70E-01	2.47E-02	0.00E 00
1618 - 1619		2.15E 00	1.50E 00	7.06E-02	1.06E-02	0.00E 00

DROP SAMPLER DATA

BURN # 3

SAMPLE TIME (GMT)	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18
1600 (BKG)	1.3	0.112	0.019	0.004	0.001	0.000	0.000	0.000	0.000
1658	0.213	0.064	0.014	0.005	0.001	0.001	0.000	0.000	0.000

BURN # 6

SAMPLE TIME (GMT)	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18
1450 (BKG)	1.0	0.133	0.028	0.010	0.004	0.001	0.000	0.000	0.000
1717	8.7	0.395	0.040	0.010	0.003	0.002	0.001	0.001	0.002
1730	2.5	0.263	0.047	0.014	0.002	0.004	0.000	0.000	0.001

BURN # 8

SAMPLE TIME (GMT)	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18
925 (BKG)	5.1	0.161	0.037	0.024	0.012	0.008	0.002	0.002	0.000
1109	29.1	1.3	0.102	0.013	0.000	0.004	0.000	0.004	0.000

BURN # 9

SAMPLE TIME (GMT)	#/CC PER INDICATED DIAMETER SIZE RANGE (MICRONS) 0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18
1506 (BKG)	22.7	0.495	0.060	0.023	0.016	0.003	0.003	0.000	0.000
1513	922	1.6	0.080	0.000	0.000	0.000	0.000	0.000	0.000
1614	93.3	0.546	0.049	0.024	0.002	0.004	0.002	0.000	0.000

APPENDIX C

Cruise track, Location of Shipboard Instrumentation and Plume photographs.
Key to instrumentation:

A. Mass loading filter and casella impactor sampling sites (Calspan).
B. PMS aerosol spectrometer probes (NRL).
C. Microwave radiometer for breaking wave measurements (NRL).
D. Drop Sampler (Calspan).
E. Usual sampling site for Drop Sampler.
F. Casella impactor sampling sites (NRL).
G. Instrument trailer (NRL).
H. MRI nephelometer sample inlet (Calspan).
I. MRI nephelometer sample inlet (NRL).
J. Aerosol inlet line to EAA and Royco aerosol analyzers (Calspan).
K. Aerosol inlet line to Mobility Analyzer (NRL).
L. HSS Nephelometer (NRL).
M. Nephelometer (NRL).
N. Dew Point Hygrometer (NRL).
O. Wind sensors for correlation to breaking wave measurements (NRL).
P. Turbulence probes for wind speed, temperature and humidity (Argonne Nat. Lab.).
Q. Verticle profile temperature probes (Calspan).
R. Cup annemometer and wind vane (Calspan).
S. Ships wind sensors.

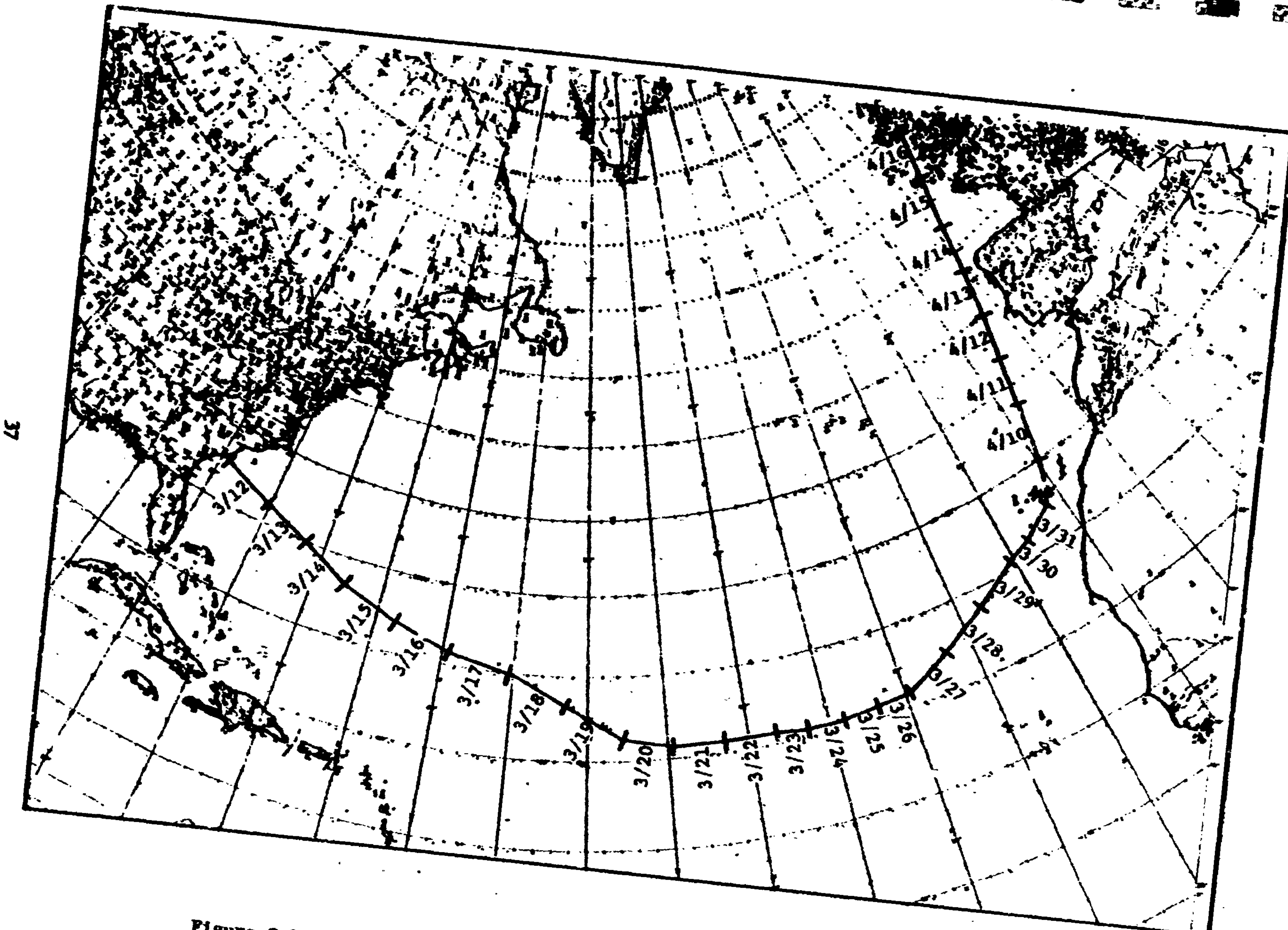


Figure C-1. Cruise Track; NRL Atmospheric Physics Cruise, March-April 1983.

Figure C-2 THE USNS LYNCH, 20 MARCH 1983

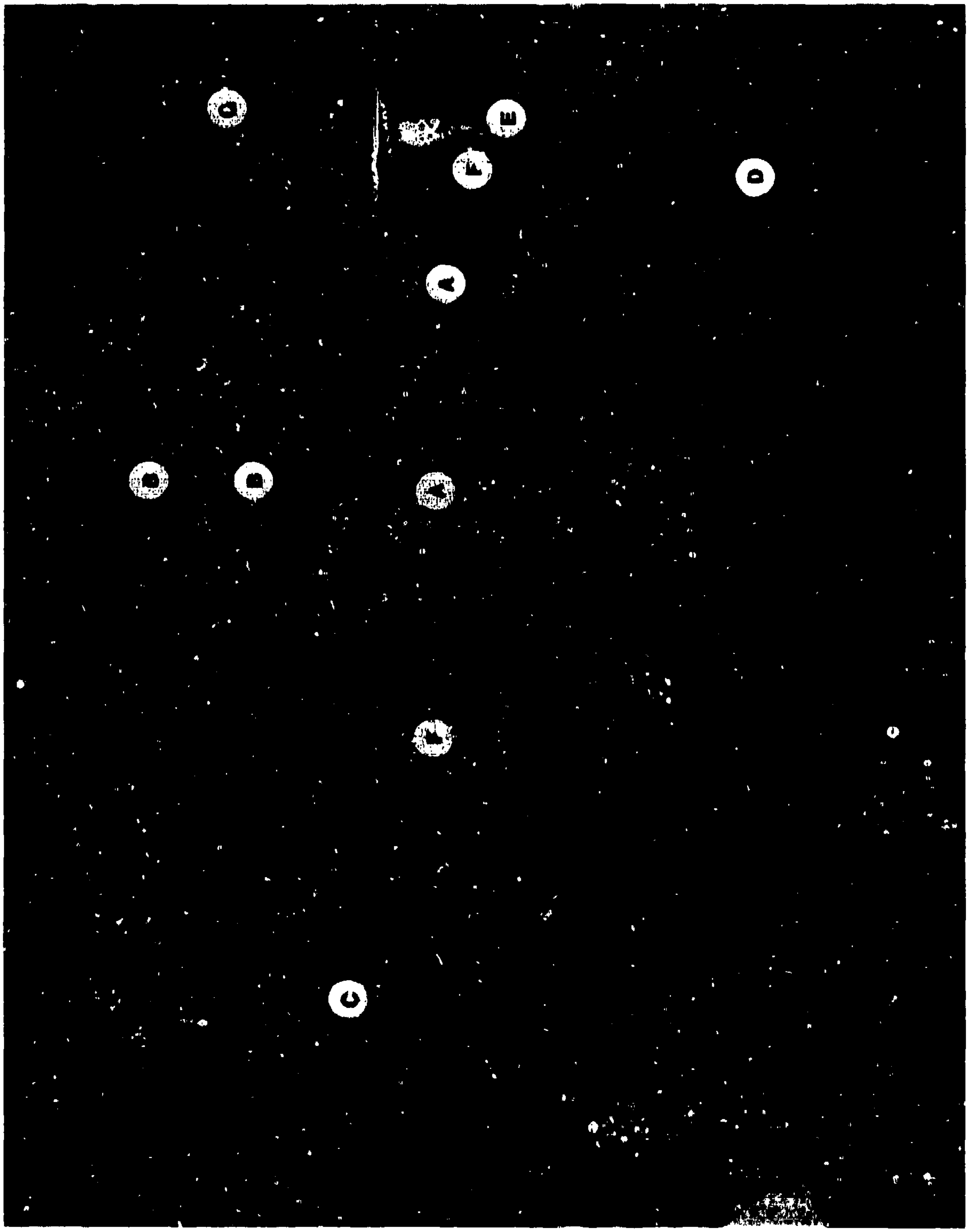


Figure C-3 BOW MOUNTED EQUIPMENT AND INSTRUMENTATION

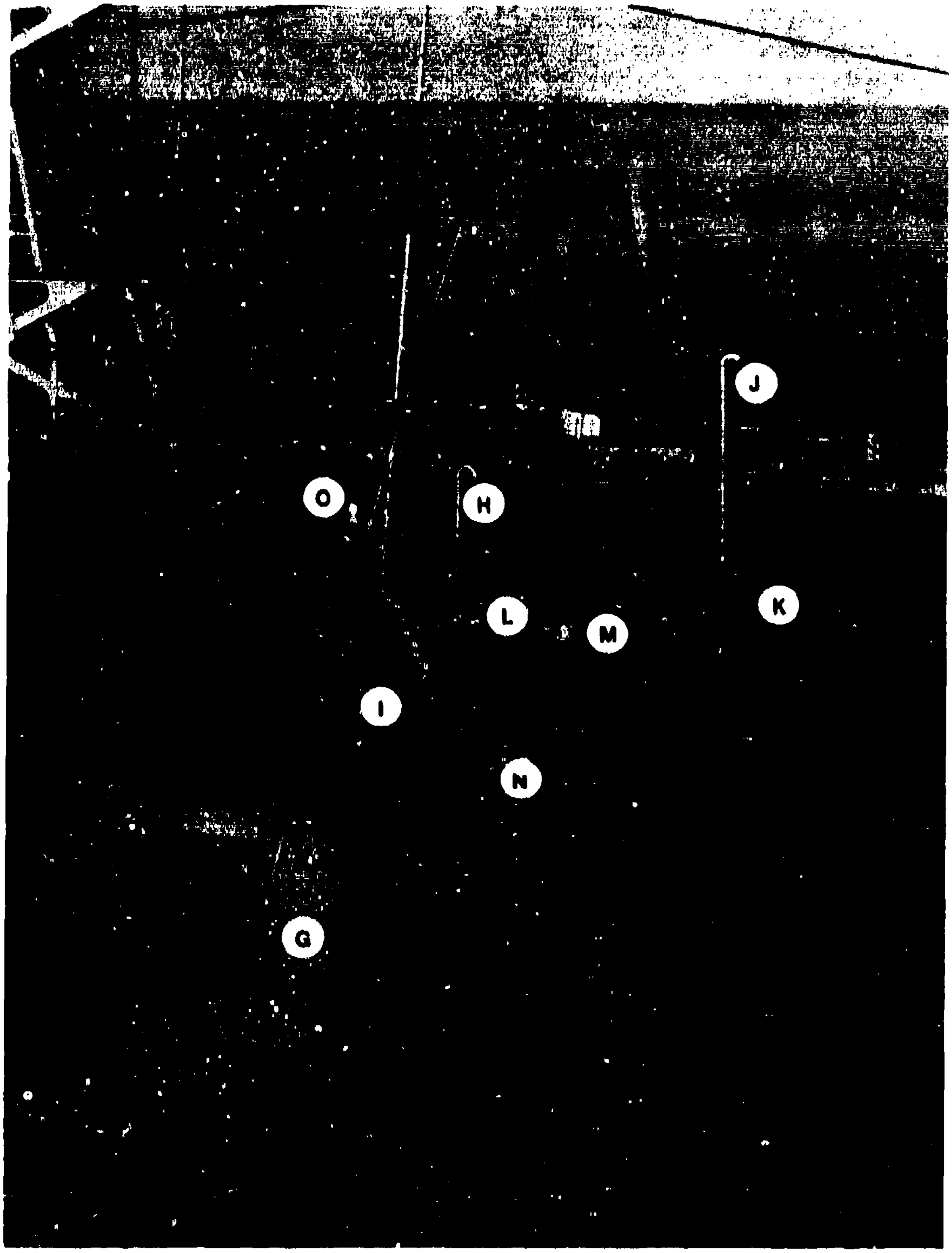


Figure C-4 NRL's INSTRUMENT TRAILER AND ASSOCIATED INSTRUMENTATION AND SAMPLE LINES.

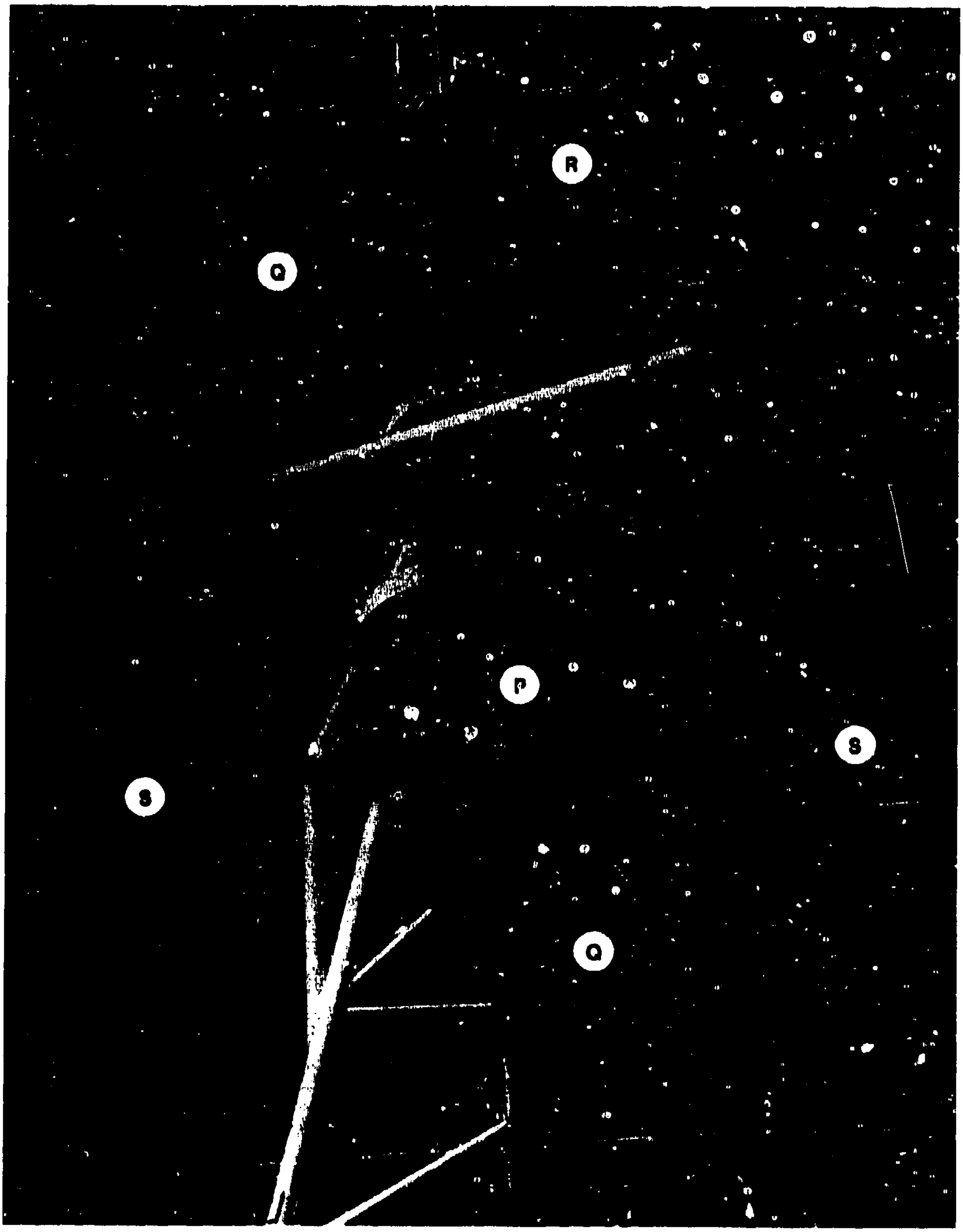


Figure C-5 MAST MOUNTED INSTRUMENTATION

Figure C-6 CANISTER CONTAINING 160 POUNDS OF THE CY85A PYROTECHNIC. AgI IGNITOR POSITIONED IN CENTER

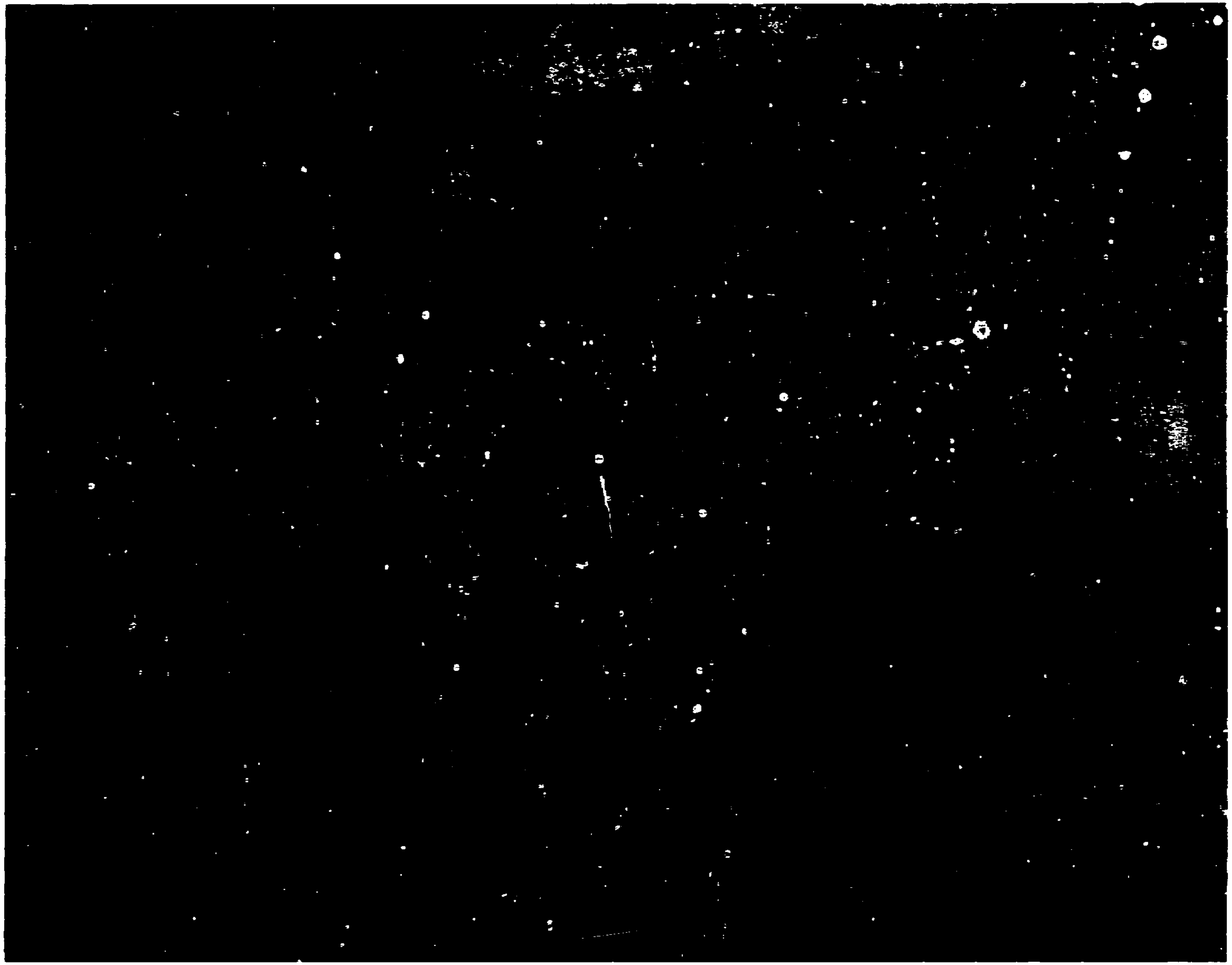


Figure C-7 SMOKE PLUME BEING PRODUCED DURING BURN NO. 7. SHIP UNDERWAY AT APPROXIMATELY 8 KNOTS

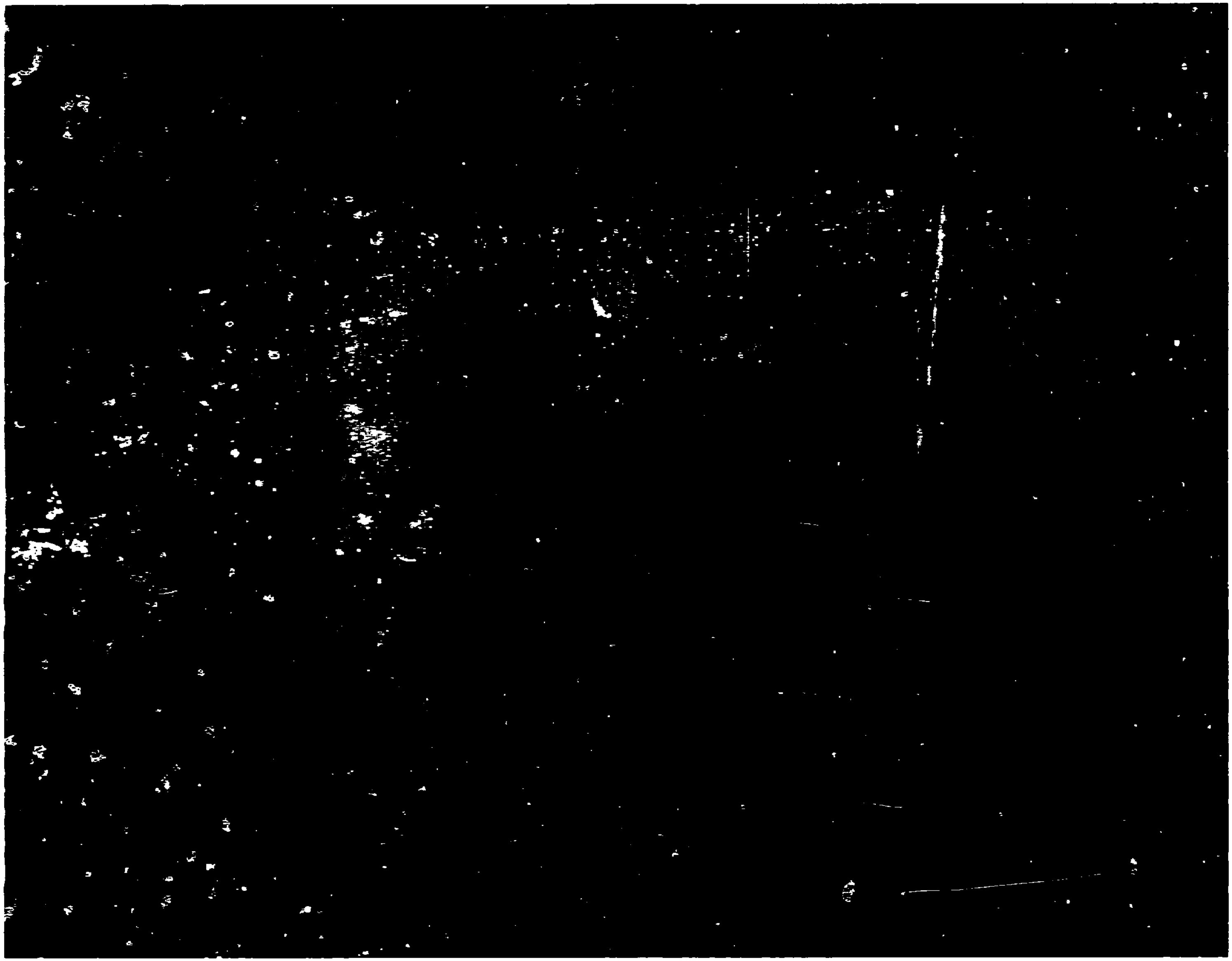


Figure C-8 SMOKE PLUME BEING PRODUCED DURING BURN NO. 3; SHIP TURNING TO ENTER SMOKE

Figure C-9 PILLARING SMOKE PRODUCED DURING BURN NO. 1; WINDS CALM, SHIP AT REST